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Increasing Cold Weather Masonry Construction Productivity

Charles J. Korhonen, Robert D. Thomas, and Edel R. Cortez August 1997

Abstract: The thermal protection requirements for cold weather masonry, as established in current industry specifications, were evaluated. Experiments were conducted to define the most relevant factors in the process of freezing of newly placed mortar. The effect of unit absorption on the moisture content of mortar during the first hours after assembly was assessed. Correlations of moisture content with time were developed for mortar in contact with masonry units. Frost immunity thresholds in terms of mortar moisture content and in terms of maturity were determined. The test results provided the basis for new proposed guidance on when fresh mortar can be safely exposed to freezing temperatures. Test methods for evaluation of the freeze–thaw resistance of masonry units were evaluated. A new test was proposed and adopted by ASTM as a new standard test for the freeze–thaw testing of masonry units. In addition, several chemicals were evaluated for their potential as antifreeze admixtures for masonry mortar. Antifreeze admixtures were first developed for use in concrete, but the practicality of using antifreeze admixtures in masonry mortars was demonstrated in a field application in Michigan during the winter.

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US Army Corps
of Engineers®
Cold Regions Research &
Engineering Laboratory

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August 1997

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Charles J. Korhonen and Edel R. Cortez, Research Civil Engineers, Civil and Geotechnical Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory, and Robert D. Thomas, Director of Research, National Concrete Masonry Association.

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Increasing Cold-Weather Masonry Construction Productivity

CHARLES J. KORHONEN, ROBERT D. THOMAS, AND EDEL R. CORTEZ

INTRODUCTION

Background

Since 1970, the International Masonry Industry All-Weather Council (IMIAWC) has provided guidance for cold weather masonry construction (IMIAWC 1988). Among other things, IMIAWC recommends that fresh mortar not be placed on snow- or ice-covered surfaces, and that it be maintained above freezing for 16 to 24 hours after placement. Low temperatures can slow the strength gain of mortar, and sufficiently low temperatures can permanently damage it. Though fresh mortar can develop apparent strength while frozen, this strength dramatically degrades when the mortar is thawed.

In its guide specifications, the Council requires that the moisture content of newly placed mortar be reduced to a maximum of 6% prior to discontinuing heating. The guide specification does not provide guidance on the time needed for typical masonry mortars to reach the required moisture content. In addition, heating mortar ingredients, especially water, up to 50°C (122°F) is recommended to assist in frost protection.

The recommendations contained in the guide specification were based on the experience and empirical data available at the time it was written. As a result of limited experimental data, the guidance is quite conservative. It constitutes a safe approach to uncertainty, but results in significant cost penalty. This research project has produced experimental data that can lead to a safe reduction in thermal protection.

The minimum cold weather protection is no thermal protection at all. This can only be achieved with the help of antifreeze admixtures. Antifreeze admixtures have been successfully used in concrete (Korhonen et al. 1994). Since masonry mortars are also portland-cement-based, it seems reasonable to investigate the application of antifreeze admixtures to masonry mortar as well. However, there are significant differences between concrete and mortar that must be considered. As little water as possible is used in the preparation of concrete. In contrast, high water contents in mortar are not of concern during mixing because the concrete masonry units on which the mortar is placed draw free water out of the mortar. This suction of water from mortar results in a rather open pore structure in the hardened mortar. The aggregates used in concrete are also much coarser than those used in mortar. For these and other reasons, while positive experiences with admixtures in concrete provide promise for their use in masonry mortar, testing is certainly required to demonstrate their effects on masonry mortar.

Objectives

The intent of this project was to develop improved cold-weather masonry criteria, construction procedures, and guide specifications that minimize excessive protection requirements for newly installed masonry, thus resulting in improved long-term freeze–thaw durability and economy. The specific objectives were:

1. Evaluate cold-weather performance of masonry,
2. Evaluate antifreeze admixtures for masonry mortars, and
3. Update guide specifications for cold-weather masonry.

To evaluate the cold-weather performance of conventional masonry systems, experiments

were planned to define the parameters that determine whether a newly placed masonry system will be harmed by cold weather. The active ingredient in the mechanism of frost damage is water. Therefore, the experimental work followed the moisture content of mortar and masonry units from the mixing operation to the masonry assembly stage through the curing period. The experiments also evaluated the practicality of using antifreeze admixtures, originally designed for cold-weather concrete, in masonry mortars. The final objective was to transfer findings through reports, conference papers, and updates to masonry construction manuals.

Approach

The experimental work in this project consisted of two major stages: a series of laboratory experiments, and a field application. As shown in Figure 1, the laboratory experiments were divided into two sections. Section 1 evaluated the effect of low temperatures on conventional masonry, and section 2 evaluated the usefulness of antifreeze admixtures. The laboratory experiments were a series of tests, each designed to produce information useful to better define the minimum thermal protection requirements for cold weather masonry construction. The test results enhanced our knowledge of the mechanisms of freezing and the moisture regime of typical masonry built in cold weather. The field application demonstrated the use of antifreeze admixtures in winter masonry construction.

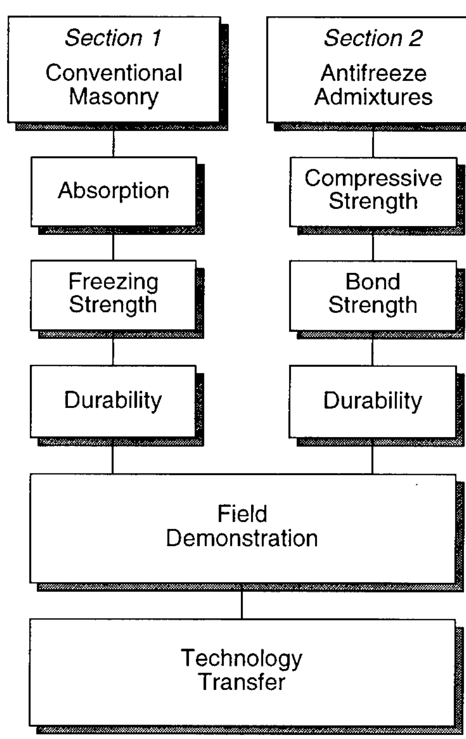


Figure 1. Research plan.

LABORATORY EXPERIMENTS

Absorption

Objective

Dry mortar is immune to frost damage; water-saturated mortar is susceptible to frost damage. At the time of placing, mortar is water saturated, and therefore frost susceptible. To define the transition between susceptibility and immunity, three fundamental parameters needed to be defined: a) the maximum water content that mortar can have without frost damage, b) the time needed for mortar to dry to any given moisture content, and c) the major factors that determine the rate of mortar moisture loss. One of these factors is the absorption of mortar moisture by the masonry units. The objective of this section of the report is to develop correlations of mortar moisture content versus time for mortar placed between typical masonry units.

Mortar types and mixture proportions

ASTM C 270 lists four types of mortar (M, S, N, and O) specified under each of two types of cement blending methods: on-the-job blending of portland cement and lime (PCL), and factory preblended masonry cement (MC). Two mortar mix design methods are in common use: the proportion method and the property method. The proportion method specifies certain volumes of portland cement, hydrated lime, and sand to be mixed with water to achieve a certain degree of workability. Alternatively, prebagged masonry cement (MC) can be used together with sand and water to achieve the same effect. The property method allows for the use of alternative volume combinations, provided laboratory test mortar achieves the prescribed values for strength, water retention, and air content. The proportion method was used for the mortar mix designs of this project.

Hydration and strength development rates are reduced as ambient temperatures drop. Generally, no specific rules are given for selecting a mortar type for use at low temperatures. However, it is acknowledged that higher portland cement contents promote higher strengths at low temperatures compared with similar mortars

Table 1. Mortar mixture volumetric proportions.

Type	*Portland cement, type I*	*Hydrated lime*	*Masonry cement*	*Masonry sand*
PCL-M	1.00	0.25	—	3.75
PCL-N	1.00	1.25	—	6.75
MC-M	—	—	1.00	3.00
MC-N	—	—	1.00	3.00

Table 2. Specific gravity and density of mortar ingredients.

Ingredient	*Specific gravity*	*Bulk density (kg/m^3 [lb/ft^3])*
Portland cement	3.15	1507 (94)
Masonry cement, type M	2.97	1271 (80)
Masonry cement, type N	2.95	1122 (70)
Lime	2.34	641 (40)
Masonry sand	2.67	1271 (80)

containing low amounts of portland cement. Thus, two of the four mortar types from the portland cement–lime (PCL-M and -N) and the masonry cement (MC-M and -N) proportioning methods were chosen for testing. The type M mortar contains more portland cement than does type N.

The mixture proportions of the four mortars studied are given in Table 1 based on bulk volumes as specified in ASTM C 270. Table 2 provides the physical values used to determine batch weights for each study.

Experimental approach

Lower water contents in mortar result in improved resistance to damage from freezing. Because concrete masonry units are porous in nature and have an affinity for drawing moisture from masonry mortar, the absorptive properties of the masonry unit may play an important role in the performance of masonry assemblies in cold weather.

Immediately after fresh mortar is placed in contact with the masonry unit, the masonry begins to draw free water from the mortar. Over time, water loss in the mortar continues due to prolonged contact with the masonry unit, evaporation to the air, and hydration of the cement within the mortar. We evaluated the rate of water loss by the mortar as it is affected by contact with the concrete masonry unit. Several different unit types with a range of unit properties, moisture contents, and temperatures were used to document this effect.

The rate of absorption of water by masonry units was also compared with their rate of absorption of free water (determined through partial unit immersion in accordance with the initial rate of absorption procedures of ASTM C 67) as well as with the total absorption potential of the unit (determined through full unit immersion in accordance with the absorption procedures of ASTM C 140). If there is a correlation between absorption of water from mortar to either of these standardized procedures, the values of those standard procedures can be used to predict the rate of mortar water loss.

Full unit immersion tests

The absorption procedures within ASTM C 140 involve the full immersion of units in water maintained at approximately 20°C (68°F) for a period of 24 hours. After 24 hours, the assumption of the test method is that the unit has absorbed as much water as it will ever absorb as a result of the pressure created by the water in the tank. While immersed, the unit is weighed suspended so that its buoyancy force can be evaluated to determine the volume of water it displaces. Once removed from the tank, the unit is weighed in air in a saturated, surface-dry condition and then placed into an oven maintained at approximately 107°C (225°F) for not less than 24 hours. The oven dry weight of the unit is then recorded. The test method provides two methods of expressing the total amount of water that the unit could absorb. The first is absorption expressed as the volume of water absorbed per net volume of solid concrete material. The second method is absorption expressed as the weight of water absorbed per dry weight of material presented on a percentage basis. For concrete masonry units, the first method is preferred.

The absorption values for a concrete masonry unit are affected by a number of production variables including gradation of the aggregates used, mix water content, amount and types of cement, admixtures and other materials used, production machine type and settings, and even unit configuration. All of these variables affect how well a unit can be compacted. However, the variable that has the most influence on the absorption of the unit is the type of aggregate(s) used in its manufacture. Lighter-weight aggregates tend to be more porous and therefore have more air voids that can be filled with water. The industry standards for concrete masonry units include maximum absorption limits as a means of ensur-

Table 3. Allowable absorption values for concrete masonry units.

Unit weight classification	*Light weight (kg/m³)*	*Medium weight (kg/m³)*	*Normal weight (kg/m³)*
Unit oven-dry density	< 1680	1680 to 2000	>2000
Max. allowable absorption	288	240	208

ing adequate compaction was achieved. The higher absorptive properties of units made with lighter-weight aggregates is reflected in the sliding-scale requirements for absorption based on unit density. ASTM C 90, "Standard Specification for Loadbearing Concrete Masonry Units," includes the absorption requirements given in Table 3.

For this research, three sets of concrete masonry units, each having different absorption characteristics resulting from production differences, and one set of concrete brick were used. Representative specimens from each set were tested in accordance with the absorption procedures of ASTM C 140. The results of those tests are shown in Table 4 along with other tested parameters determined in accordance with ASTM C 140.

Partial unit immersion tests

A standard method of evaluating the water uptake capabilities of a unit partially immersed in water is included in ASTM C 67. The method involves placing a unit within a container of water such that the immersion depth of the unit is 3.2 mm ($^1/_8$ in.) for a period of 1 min. The amount of water absorbed by the unit over the 1-min period is determined by the difference in unit weight before and after immersion.

The primary force that pulls water up into the unit is capillary suction. The test method determines the effect of various parameters on water absorption including unit moisture, unit manufacture, unit surface characteristics, and water temperature (Table 5).

The units described as having "dry" moisture content had been stored in the laboratory for several months, and their moisture content at the time of testing averaged 15% of their total absorption, which is typically drier than most units used in winter construction. Those units referred to as having "normal" moisture content are perhaps nearer in water content to units typically used in winter construction. To obtain this moisture con-

Table 4. Unit properties.

Unit property (average)	*Concrete brick*	*CMU A*	*CMU B*	*CMU C*
Width, mm (in.)	91.4 (3.60)	194.1 (7.64)	193.8 (7.63)	193.5 (7.62)
Height, mm (in.)	69.1 (2.72)	193.8 (7.63)	193.5 (7.62)	192.8 (7.59)
Length, mm (in.)	188.5 (7.42)	396.5 (15.61)	396.2 (15.60)	396.5 (15.61)
Net area, top, mm² (in.²)	17,226.0 (26.7)	37,548.0 (58.2)	37,548.0 (58.2)	37,548.0 (58.2)
Net area, bottom, mm² (in.²)	17,226.0 (26.7)	42,774.0 (66.3)	42,774.0 (66.3)	42,774.0 (66.3)
Absorption, kg/m³ (pcf)	157.0 (9.8)	155.0 (9.7)	229.0 (14.3)	230.0 (14.4)
Density, kg/m³ (pcf)	2,110.0 (131.9)	2,096.0 (131.0)	1,642.0 (102.6)	1,490.0 (93.1)
Net strength, MPa (psi)	—	21.9 (3,180)	16.1 (2,340)	21.2 (3,070)

Table 5. Matrix of partial unit immersion tests.

Test no.	*Unit type*	*Unit surface**	*Unit temperature (°C)*	*Unit temperature (°F)*	*Unit moisture*	*Water temperature (°C)*	*Water temperature (°F)*	*Air temperature (°C)*	*Air temperature (°F)*
1t	CMU A	Top	20	68	Dry	20	68	20	68
1b	CMU A	Bottom	20	68	Dry	20	68	20	68
2t	CMU B	Top	20	68	Dry	20	68	20	68
2b	CMU B	Bottom	20	68	Dry	20	68	20	68
3t	CMU C	Top	20	68	Dry	20	68	20	68
3b	CMU C	Bottom	20	68	Dry	20	68	20	68
4	Brick	Side face	20	68	Dry	20	68	20	68
5	Brick	Side face	20	68	Normal	20	68	20	68
6	Brick	Side face	20	68	Wet	20	68	20	68
7	Brick	Side face	5	41	Dry	5	41	5	41
8	Brick	Side face	5	41	Dry	20	68	5	41
9	Brick	Side face	5	41	Dry	30	86	5	41

* Unit surface described based on orientation of unit as made.

tent, units were fully immersed in water for 24 hours and then allowed to dry until they averaged 50% of their total absorption. The units referred to as "wet" contained much more moisture than units typically used in winter construction. This condition was achieved by allowing saturated units to air-dry only to the point that there was little to no remaining free surface moisture present, although a large majority of the surface area was still observed to be damp. The resulting moisture content of these units averaged 85% of total absorption.

Appendix A summarizes the water uptake results. Figures 2 through 5 provide a discussion of the most important findings from the partial immersion tests.

Effect of unit moisture. The dry concrete brick absorbed nearly twice the water weight in the partial immersion test in comparison with the normal and wet units (Fig. 2). The water uptakes were nearly identical for the normal and the wet units after 1 minute of immersion time, but after 15 minutes the wet units absorbed nearly 15% more water than did the normal units.

Effect of water temperature. This comparison used dry brick. Water temperature appeared to have little effect on the ability of cold units to absorb water in the partial immersion test. As shown in Figure 3, cold units were able to absorb slightly more 20°C (68°F) water than 5°C (41°F) water and slightly more 5°C water than 30°C (86°F) water. However, there was never more

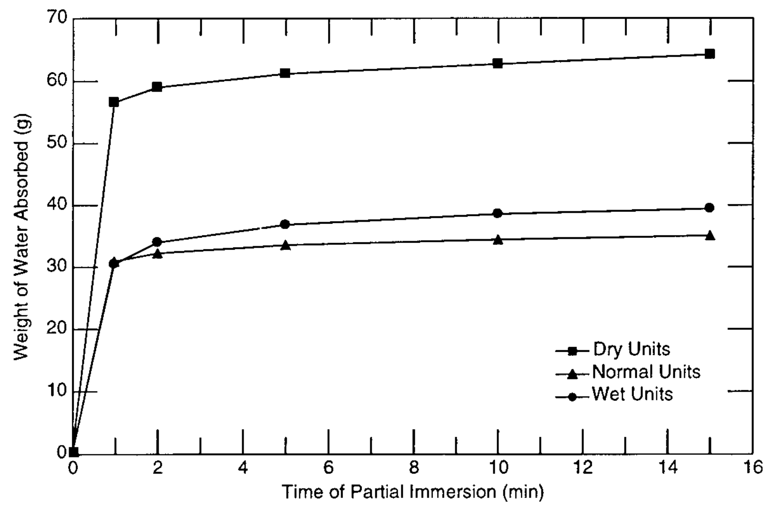


Figure 2. Effect of unit moisture on water uptake. The brick, water, and air temperatures are 20°C.

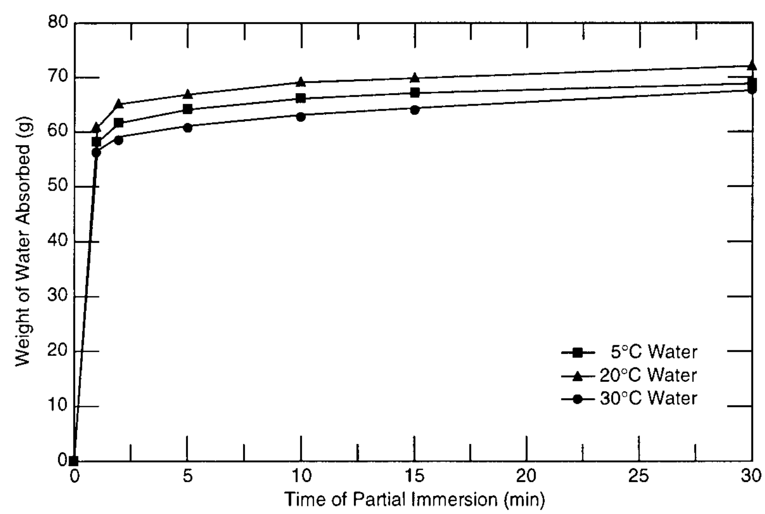


Figure 3. Effect of water temperature on water uptake. Brick and air temperatures are 5°C.

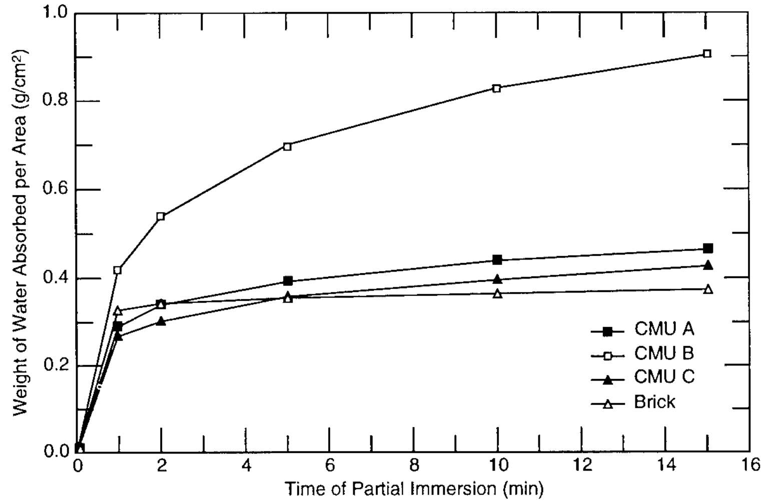


Figure 4. Effect of unit manufacture on water uptake. Unit, water, and air temperatures are 20°C.

than 7% difference between the absorption rates at any time during the test.

Effect of unit manufacture. The difference in the water uptake test results of CMU B in comparison with the other units indicates that physical unit characteristics can significantly influence capillary suction (Fig. 4). While the absorption rates (top and bottom surfaces averaged) of CMU A and CMU C were very similar, CMU B had absorbed nearly 50% more water than the other two CMUs after 1 minute and nearly 100% more water after 15 minutes. The water uptake rates of the concrete brick were more similar to those of CMUs A and C. However, while the concrete brick absorbed more water than either of these two CMUs after 1 minute, it absorbed very little additional water over the next 14 minutes of immersion in comparison with CMUs A and C such that its total absorption was less than that of the two CMU types.

Effect of absorption surface. The top and bottom surfaces of concrete masonry units can differ significantly in surface texture and appearance. The bottom surface of the unit is molded against the machine pallet during manufacture, resulting in a smooth and fine texture. The top of the unit is not molded, however, and therefore is typically rougher and more open. In concrete masonry, the mortar bed joint is in contact with both of these unit surfaces from the units above and below it. Water uptake tests were performed on both surfaces of the concrete masonry units to determine surface effects.

As shown in Figure 5, surface characteristics can have a significant influence on capillary suction. In the case of CMUs B and C, there was a difference in water absorptions of approximately 100% between the top and bottom surfaces of the same unit, with the bottom manufactured surface having the greater capillary suction. However, the results of tests on CMU A prevent drawing the conclusion that the bottom surface consistently results in increased water uptake. While the water weight absorbed by the two surfaces of CMU A were nearly identical, the smaller surface area of the top of the unit as manufactured actually gave it a greater water absorption per unit area than the bottom surface.

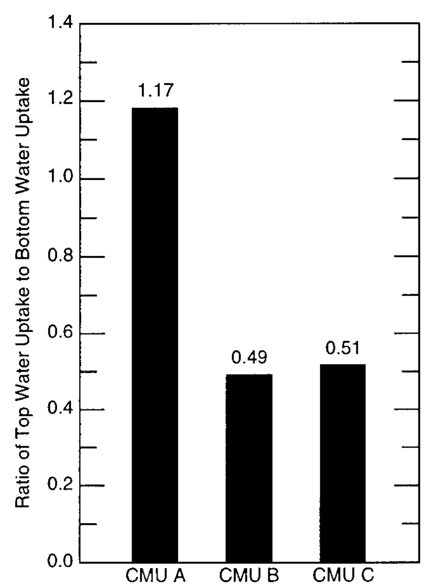


Figure 5. Effect of absorption surface on water uptake.

Mortar moisture loss tests

The rate of water loss from mortar can be affected by a number of different variables. Those variables investigated as part of this research include: unit type, unit moisture content, unit temperature, mortar type, mortar temperature, and air temperature. Among those properties *not* evaluated are the relative humidity of the air surrounding the units and the effects of wind. The testing was not structured to distinguish between mortar moisture loss attributed to absorption from the units and moisture loss attributed to evaporation to the air. To reduce the number of tests required and to facilitate laboratory constraints, most of the testing was performed using a single unit type (concrete brick) and a single mortar type (type M masonry cement mortar).

All mortar was proportioned using 2880 g of masonry sand. Batch weights of other materials (portland cement, masonry cement, and lime) were determined based on the volume proportions included in Table 1. Mortar was mixed in the laboratory using a Hobart mechanical mixer. With the exception of the type of mixer used, mixing was performed to simulate field conditions. In the field, the mason is allowed to adjust the water content of the mortar by eye to achieve the necessary mortar workability to accommodate the existing conditions at the job site. For example, on hot, windy days, the mason may use additional water in mixing to prevent premature drying of the mortar. Less absorptive units may require the mason to reduce the amount of water in the mix. Various mortar admixtures may also require the mason to adjust the mortar. Because some of the variables in these tests may affect water demand, the mason was allowed to adjust the water content as necessary to achieve the desired mortar consistency. Tests were performed on the fresh mortar to document its air content, unit weight, and consistency by cone penetration (ASTM C 780).

For all mixes involving the primary mortar type in this program, type M masonry cement mortar, no adjustments of water content were found to be necessary despite variations in the temperature of the mortar materials from 5 to 20°C (41 to 68°F). The resulting tested moisture contents for these mortars were therefore rather consistent (13.9 to 15.9%), as were the cone penetrations. It was found that more water was required to obtain a similar mortar consistency in the portland cement and lime mortars—particularly for the PCL type M mortar, which contains a greater proportion of cementitious materials than the other mortars.

The mortar was used to fabricate two prisms each with two units separated by a single full mortar bed joint. The mortar was placed on the top of the bottom brick using a mortar template to achieve a uniform joint thickness and to reduce workmanship variations between prisms. The second brick was then carefully placed onto the mortar joint and the joint was compacted using a 1.8-kg (4-lb) drop hammer to apply an impact force to the top brick. Using the same mortar, the second prism was then fabricated in the same manner. Prism fabrication was completed within 10 minutes after mortar mixing.

Five minutes after the first prism was fabricated, the top unit was removed from the prism and the exposed mortar joint was cut into a grid. One of the grid segments was sampled using a spatula and measured for moisture content. Approximately 30 g of mortar was sampled, placed on a ceramic plate, and dried in a microwave oven. The moisture content was calculated based on the difference between the initial weight of the mortar compared with its final dry weight. The top brick was placed back on the exposed mortar joint, and the prism remained undisturbed until the next sampling time. This procedure was repeated at 5, 15, 30, 45, 60, 120, 240, and 1440 min.

These procedures were used to evaluate the effects of unit temperature, unit moisture content, mortar type, mortar temperature, and air temperature on the rate of mortar water loss. Similar procedures were used with several different concrete masonry units to investigate the effects of unit manufacturing. The matrix of combinations used to achieve this information is listed in Table 6. Two prisms were fabricated for each of the combinations shown.

Different mortar temperatures were achieved by heating or cooling the mortar materials (cement, sand, water) before the mortar was mixed. Unit temperatures were achieved by the same method. Two different air temperatures were used, 5 and 20°C (41 and 68°F). Those prisms that were kept at 20°C (68°F) were stored in the open lab air for the duration of the test. Those prisms kept at 5°C (41°F) were placed within an environmental chamber maintained at that temperature. Because the chamber requires air circulation to maintain specified temperatures, the prisms were sealed in plastic bags to prevent wind effects from influencing the loss of moisture from the mortar. At the specified sampling times, the prisms were removed from the chambers, the bags were opened, the mortar sample was taken, and the prisms were

Table 6. Matrix of mortar moisture loss tests.

Test no.*	Unit type†	Unit temperature (°C)	Unit temperature (°F)	Unit moisture	Mortar type	Mortar temperature (°C)	Mortar temperature (°F)	Air temperature (°C)	Air temperature (°F)
1	Brick	20	68	Dry	MC-M	20	68	20	68
3	Brick	20	68	Dry	MC-N	20	68	20	68
4	Brick	20	68	Dry	PCL-M	20	68	20	68
6	Brick	20	68	Dry	PCL-N	20	68	20	68
7	Brick	20	68	Dry	MC-M	5	41	5	41
8	Brick	20	68	Dry	MC-M	20	68	5	41
9	Brick	20	68	Dry	MC-M	30	86	5	41
10	Brick	5	41	Dry	MC-M	5	41	5	41
11	Brick	5	41	Dry	MC-M	20	68	5	41
12	Brick	5	41	Dry	MC-M	30	86	5	41
13	Brick	20	68	Normal	MC-M	5	41	5	41
14	Brick	20	68	Normal	MC-M	20	68	5	41
15	Brick	20	68	Normal	MC-M	30	86	5	41
16	Brick	5	41	Normal	MC-M	5	41	5	41
17	Brick	5	41	Normal	MC-M	20	68	5	41
18	Brick	5	41	Normal	MC-M	30	86	5	41
19	Brick	20	68	Wet	MC-M	5	41	5	41
20	Brick	20	68	Wet	MC-M	20	68	5	41
21	Brick	20	68	Wet	MC-M	30	86	5	41
22	Brick	5	41	Wet	MC-M	5	41	5	41
23	Brick	5	41	Wet	MC-M	20	68	5	41
24	Brick	5	41	Wet	MC-M	30	86	5	41
28	CMU A	20	68	Dry	MC-M	20	68	20	68
29	CMU B	20	68	Dry	MC-M	20	68	20	68
30	CMU C	20	68	Dry	MC-M	20	68	20	68

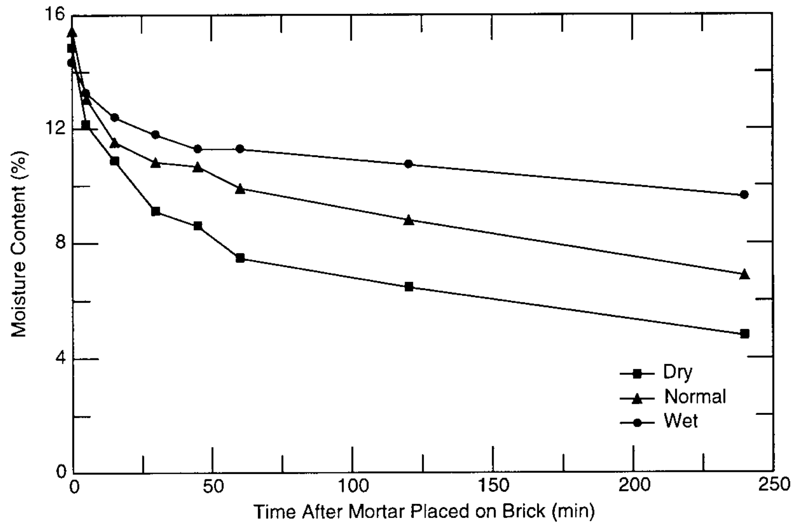
* Several of the initially planned tests were not performed (2, 5, 25, 26, 27).
† Unit properties are listed in Table 4.

placed back into the bags and returned to the cooling chamber.

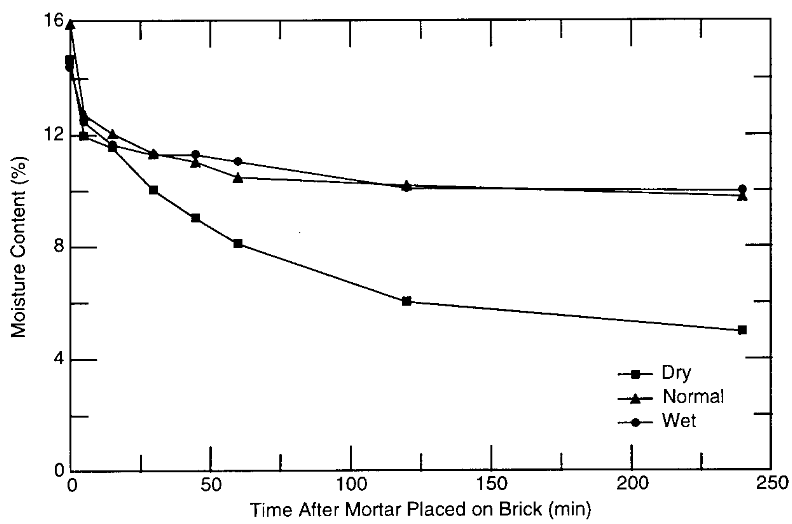
Appendix A summarizes the results of the mortar moisture loss tests. Figures 6 through 10 present the significant findings from the tests.

Effect of unit moisture. The effect of masonry unit moisture content on mortar moisture loss was measured using six different combinations of mortar and unit temperature. In all six cases, mortar in contact with the dry units exhibited a much greater rate of moisture loss than with either the normal or the wet units. In addition, in all six cases, as expected, the wet units resulted in the lowest rate of mortar moisture loss. While the moisture loss of the mortar in contact with normal units was always greater than that in contact with wet units and lower than that in contact with dry units, the relationships between them were not always consistent. In two of the six cases, the mortar moisture loss was approximately equal to the average of that with the dry and wet units, as exemplified in Figure 6a. In the other four cases, there was essentially no difference in mortar moisture loss between the normal and the wet units, as shown in Figure 6b.

The tests plotted in Figure 6 were all cured in sealed bags in the cooling chamber, as were all tests conducted at 5°C (41°F) air temperatures. It is reasonable to assume that throughout the test the mortar was losing moisture not only to the units in which it was in direct contact, but also to the air within the bag. The wetter the unit, the quicker the buildup of relative humidity within the bag, which reduced subsequent moisture loss from the mortar to the humid air. Condensation within the plastic bags during the tests supports this contention. The effect of bagging the prisms can be seen in Figure 7. Due to handling, the bag surrounding one prism developed a hole that permitted moisture within the bag to escape. The effect of the vented bag resulted in a significant reduction in mortar moisture content in comparison with the mortar in the other prism. At the conclusion of the 24-hr test, both prisms were removed from their bags and returned to the cooling chamber. The rate of moisture loss from the mortar in the unvented prism then increased significantly, but the rate of moisture loss from the mortar in the vented prism was virtually unaffected. Within several hours, the moisture contents of both prisms stabilized at an



a. 20°C units.



b. 5°C units

Figure 6. Effect of unit moisture on mortar moisture loss using 20°C and 5°C units. Mortar (MC-M) and air temperatures are 5°C.

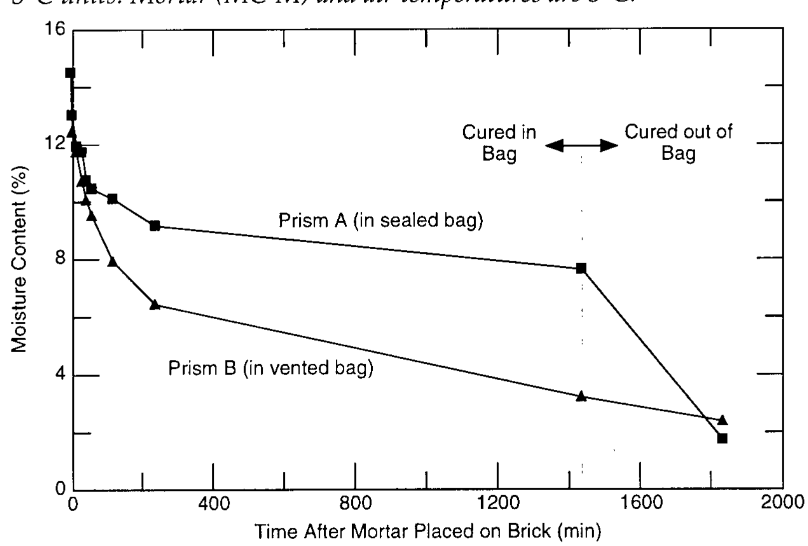


Figure 7. Effect of bagged test condition on test no. 14. Units and mortar (MC-M) at 20°C, air temperature of 5°C.

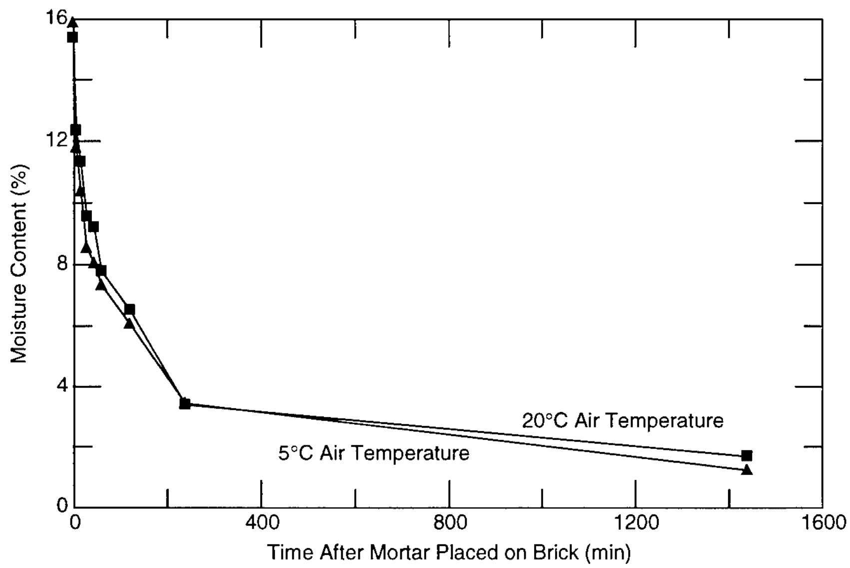


Figure 8. Effect of air temperature on rate of moisture mortar loss. Dry units and mortar (MC-M) at 20°C.

approximately equal value. The removal of the unvented prism from its bag and the venting of the bag around the other prism resulted in a lower relative air humidity around the prisms, which increased the rate of water loss to the air by both the mortar and the units. The air circulation would also contribute to increased evaporation. As the units continued to dry due to these two factors, the units were also then capable of absorbing more water from the mortar.

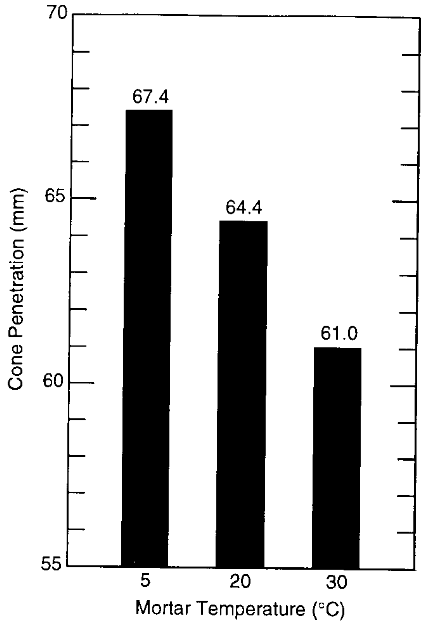
Effect of air temperature. While air temperature obviously influences many aspects of masonry construction, air temperature by itself does not appear to have a significant direct effect on the rate of moisture loss in the masonry mortar (as long as those temperatures are above the freezing point of the water). The effect of reducing air temperature from 20 to 5°C (68 to 41°F) using warm units and warm mortar is shown in Figure 8.

Effect of mortar temperature. Mortar temperatures of 5, 20, and 30°C (41, 68, and 86°F) were used with units of different moisture contents and different unit temperatures in different air temperatures. Based on the results of these tests, there appears to be little effect of mortar temperature on rate of mortar moisture water loss (Fig. 9). A slightly increased rate of water loss in the 30°C (86°F) mortar was observed in comparison with the other mortar temperatures when used with the warm units. However, when cold units were used, the mortar with a temperature approximately equal to that of the units appeared to have the slightly greater rate of water loss.

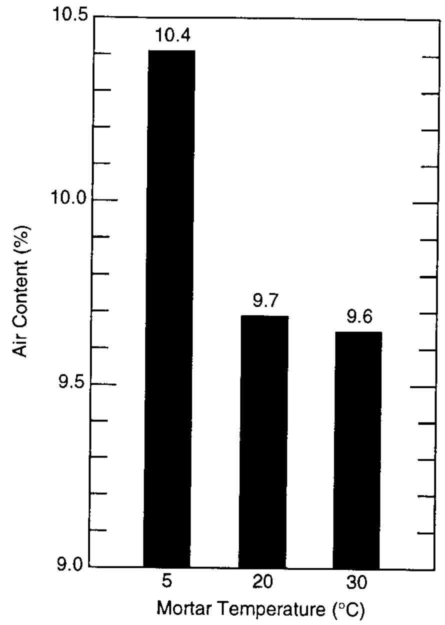
The effects of mortar temperature were evident in the results of tests performed on fresh mortars. Cone penetrations were consistently lower for higher-temperature mortars and, correspondingly, air contents decreased with increases in temperature (mortar water contents were maintained equal).

Effect of unit manufacture. The results of the full immersion tests and the partial immersion tests as well as other individual tests on the various units considered confirmed that each unit has very different unit properties. The results of the absorption from mortar tests, as shown in Figure 10, demonstrate that these different properties also affect the rate of mortar moisture loss. The results correspond rather well to those of the partial immersion test results. The partial immersion test demonstrated the wicking or suction potential for the units. CMU B demonstrated the greatest such potential in those tests, and the effect of that potential is shown in Figure 10 by working to reduce the moisture content in the mortar at a faster rate than the other unit types.

Effect of unit temperature. In nearly all of the nine cases in which the effect of unit temperature could be evaluated, the units with the higher unit temperature resulted in the greater rate of unit moisture loss. However, for the majority of those cases, the increased rate of mortar moisture loss was negligible. The only cases in which there appeared to be a real benefit to the warmer units was when they were used with 30°C (86°F) mortar. This research did not address the effects of unit temperatures below the freezing point of water, 0°C (32°F).



a. Initial cone penetrations



b. Air contents.

Figure 9. Effect of mortar temperature.

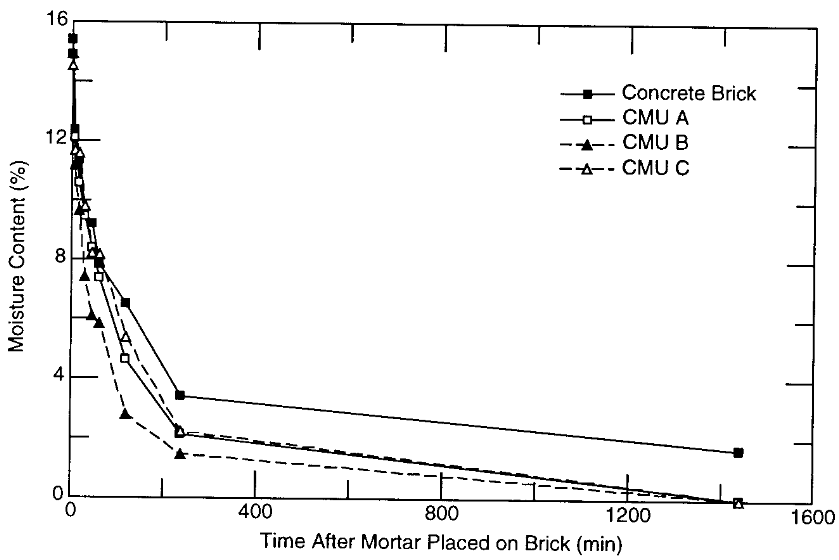


Figure 10. Effect of unit manufacture on rate of mortar moisture loss. Unit and mortar (MC-M) temperatures are 20°C.

Comparison of water absorption test methods

While there does not appear to be a good relationship between the results of the full immersion absorption test and the results of either of the two other absorption test methods performed, there does appear to be a rather promising relationship between the results of the partial immersion tests and the mortar moisture loss tests. These results could support the use of the partial immersion tests to predict the effects of concrete masonry units on the rate of moisture loss by a masonry mortar. For the partial immersion tests performed, the following conclusions about the mortar moisture loss tests could have been accurately estimated:

- The relative relationship between the rate of mortar moisture loss to the different units evaluated
- The relative relationship between the effect of unit moisture content on mortar moisture loss
- The lack of significant influence of mortar temperature on mortar moisture loss.

Freezing strength

Objective

Mortar is most susceptible to frost damage at early age because: a) its pore structure is underdeveloped, and b) its moisture content is high. Based on these two conditions, two experiments were devised to establish thresholds of when mortar can withstand one cycle of freezing and thawing. The objective was to determine these thresholds in terms of moisture content or in terms of maturity.

Critical moisture

As stated above, the moisture content of mortar is a critical factor during early-age freezing. Mortar is typically mixed to a moisture content of between 13 to 16%, but due to evaporation, absorption into masonry units, and cement hydration, its moisture content declines. Current guidance is based on the premise that mortars that are frozen while they contain more than 6% moisture will be frost damaged and subsequently never develop full strength. Conversely, it is believed that mortars with moisture contents below 6% are frost resistant. This section evaluated the effect of freezing on fresh mortar in an attempt to identify the maximum moisture content that mortar may have and still be immune to one event of freezing.

The four mortar types described earlier were made into several batches, each containing a different moisture content. Once mixed, the mortars were cast into 50- × 100-mm (2- × 4-in.) plastic cylindrical molds. The mortar was placed into the cylinders in three equal lifts and was consolidated using a vibration table. This method of cylinder consolidation overcame many of the difficulties of dealing with the different moisture levels between the mortar batches. Once consolidated, the filled cylinder molds were capped with plastic lids and placed into a –20°C (–4°F) room overnight. The next morning the cylinders were moved into a 20°C (68°F) room. After 28 days, not including the time in the cold room, the mortar cylinders were stripped from the plastic molds and tested for compressive strength. Control cylinders from each batch that were not subjected to freezing temperatures were tested at an equivalent age.

Figure 11 presents the compressive strength test results from the four mortars made with five different moisture contents. As can be seen, all mortars were unaffected by being frozen at moisture contents of 6 and 8%, and each had a 28-day strength that was equal to or greater than that of the control mortar. In fact, the mortars performed better, compared with the control, when frozen at 8% moisture contents than when frozen at 6%. The effects of frost damage started to become evident at a moisture content of 10%. At that level, the portland cement–lime mortars suffered a 9 to 12% loss of strength, but the masonry cement mortars were largely unaffected. (Microscopic examination showed the masonry cement mortars contained entrained air bubbles. The portland cement–lime mortars did not contain entrained air.) At moisture contents of 12% and above, all mortars showed some, though not significant,

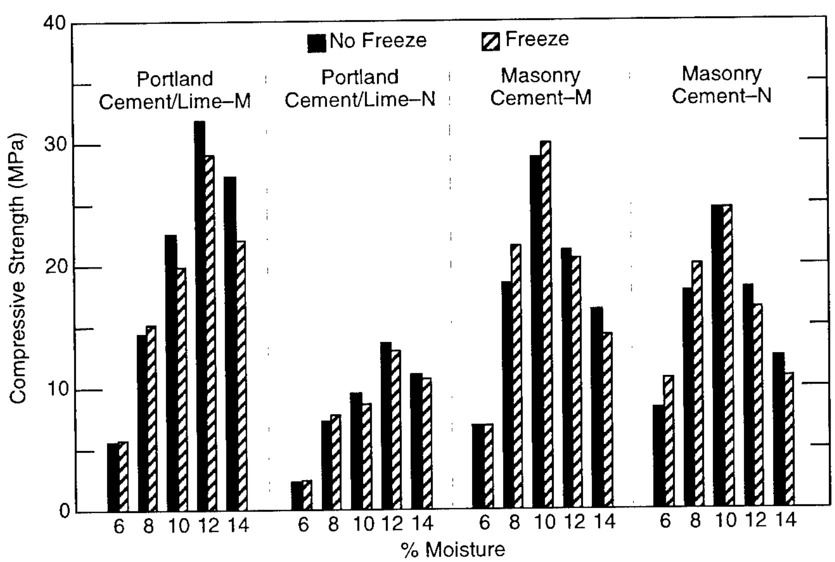


Figure 11. Critical moisture.

damage from early-age freezing. Interestingly, the strongest portland cement–lime mortars resulted from a moisture content of 12%, and the strongest masonry cement mortar came from a moisture content of 10%. Moisture contents above and below these levels weakened the mortar. Despite efforts to mix and consolidate all of the batches equally regardless of the mixing water content, difficulties in working with drier mortar batches may account for some of the reductions in strength of the mortars with lower water-to-cement ratios.

Critical maturity

The development of pore structure in mortar is another mechanism that produces frost resistance. As a mortar matures, its water chemically combines with cement, with the result that the mortar increases in strength and decreases in free water. At some age the quantity of freezable water falls below a critical level and creates empty pore space within the mortar that enables the mortar to accommodate water–ice expansion without damage. The objective of this experiment was to determine the age at which mortar first becomes resistant to a single cycle of freezing and thawing.

A type M masonry cement mortar was utilized for this test series. It was mixed to a 16% moisture content at room temperature according to existing standards and cast into cylindrical samples measuring 50 × 100 mm (2 × 4 in.) using vibration as the method of consolidation. All of the mortar cylinders cast for this phase of the testing were made from a single mortar batch. The test consisted of periodically bringing one set of three cylinders into a –20°C (–4°F) room for at least 24 hr followed by room temperature curing for a total of 7 days, excluding the time in the cold room. The cylinders were then stripped from their plastic molds and tested in compression. Strengths were compared with those of control samples that were never frozen. The first set of cylinders went into the cold room immediately after the samples were cast. Additional cylinders were brought to the cold room at 1-hr intervals through the first 12 hr, as well as a final set of cylinders at 48 hr. The cylinders were kept in the cold room overnight, and returned to a warm room the following afternoon.

Figure 12 shows the 7-day compressive strengths for these cylinders. The dotted line in the figure represents the 7-day strength of the control mortar that was never frozen. As can be seen, if a mortar is frozen at too early an age the mortar loses strength. However, it is also clear that once a mortar attains a certain maturity it can resist frost damage. In this case, keeping the mortar at room temperature for a minimum of $5\,^3/_4$ hr before freezing enabled the mortar not only to resist frost damage but to begin to gain strength in excess of the control. In fact, curing the mortar for 12 hr at room temperature before exposing it to freezing temperatures produced a 10% increase in strength. To confirm that there is a benefit to freezing mortar, similar testing was done with the other mortar types frozen at times between 8 and 60 hr and then cured at room temperature for 28

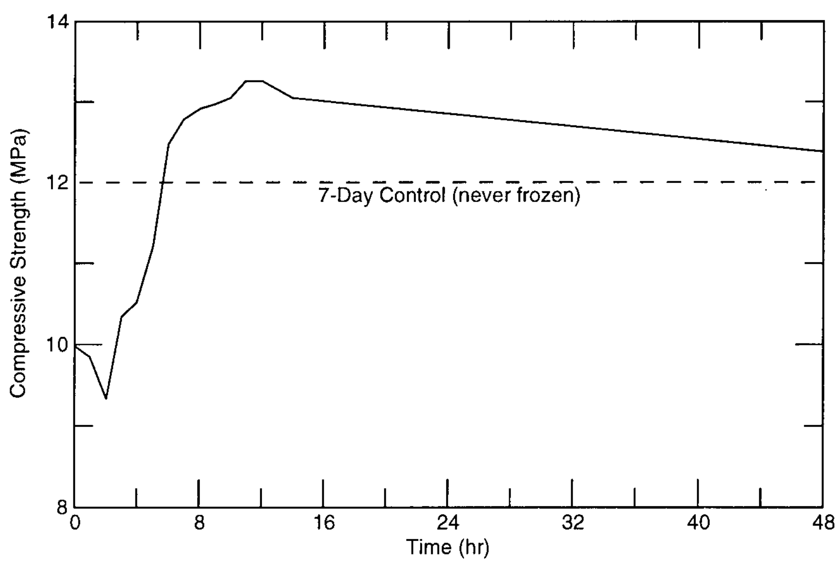


Figure 12. Critical maturity.

days. The optimum curing time was between 12 and 16 hr. Thus, early-age freezing is not always harmful. One explanation for greater strengths of mortar subjected to freezing temperatures is that these low temperatures slow the hydration of the cement, resulting in a more controlled (less violent) chemical reaction rate.

Antifreeze admixtures

Objective

The primary objective of the following tests was to assess the practicality of using antifreeze admixtures developed for concrete with masonry mortars. In addition, some alcohols were evaluated for their ability to perform as antifreeze admixtures for mortar.

Antifreeze admixtures are chemicals that protect mortar from freezing without the use of heaters. Currently, antifreeze admixtures are not recommended for use in mortar. The concern is that such chemicals will harm compressive and bond strengths or corrode embedded metals within the mortar. A similar concern existed for concrete a few years ago. Since then, certain chemicals have been shown to protect concrete from freezing without causing detrimental side effects (Korhonen et al. 1994). The objective of this section was to evaluate whether a similar result was possible for mortar. This study evaluated chemicals for their effect on low-temperature strength gain, bond strength, and the freeze–thaw durability of mortar.

Effect of temperature on strength

Experiments were conducted in the laboratory to develop data that relate strength gain to curing temperature. Strength tests were done on 50- × 100-mm (2- × 4-in.) cylinders of admixture-free mortar and mortar that contained the chemicals shown in Table 7. The calcium chloride and KC1 chemicals were dosed by weight of cement, and the two alcohols were dosed by weight as a percent replacement of water so as to maintain constant plasticity of the mortar. The mortars were mixed to a moisture content of 16%, and cylinders were cast at room temperature and brought into a given coldroom a few minutes after being cast. At the prescribed testing age, the cylinders were brought back to room temperature and compression-tested as soon as the temperature at their center of mass reached 5°C (41°F). (A dummy cylinder instrumented with a thermocouple served as the temperature reference.) Some of the test samples were kept in their respective coldrooms for as long as 28 days, then returned to room temperature for an additional 28 days (56 days curing time) to test for strength recovery.

Table 7 presents a summary of the strength test results expressed as a percentage of the same-age strength of a control, admixture-free mortar made with a type M masonry cement cured at 20°C (68°F). As seen in the 20°C results, methanol retarded strength gain, especially at higher dosages. At 7 days, methanol produced strengths that were only 47 to 79.4% strong relative to the control. At –5 and –10°C (23 and 14°F) the metha-

Table 7. Compressive strength of mortars containing various admixtures. Strengths are expressed as percentage relative to admixture-free mortar cured at 20°C (68°F).

	Curing temp. (20°C)				*Curing temp. (–5°C)*				*Curing temp. (–1°C)*			
*Admixture**	*Day 7*	*Day 14*	*Day 28*	*Day 56*	*Day 7*	*Day 14*	*Day 28*	*Day 56*	*Day 7*	*Day 14*	*Day 28*	*Day 56*
11.6% meth	79	90	94	100	8	36	63	103	0	5	29	96
17.4% meth	68	80	91	94	3	16	44	97	0	5	20	109
23.3% meth	47	63	78	92	0	6	23	91	0	0	8	105
2% $CaCl_2$, 11.6% meth	76	85	92	99	18	44	68	93	5	14	34	76
2% $CaCl_2$, 17.4% meth	67	72	87	91	12	29	51	101	4	10	22	96
2% $CaCl_2$, 23.3% meth	68	73	84	95	7	19	36	93	1	4	11	91
4% $CaCl_2$, 11.6% meth	72	80	87	91	7	33	52	95	0	4	22	88
4% $CaCl_2$, 17.4% meth	65	73	86	93	3	24	43	97	0	0	10	91
4% $CaCl_2$, 23.3% meth	55	62	79	86	2	14	34	93	0	0	5	87
1% $CaCl_2$, 23.3% IPA	68	80	94	103	5	18	37	102	0	4	17	104
17.4% IPA	83	93	100	104	2	0	31	104	0	0	2	90
6% KC1†	105	97	97	98	67	87	88	112	26	49	56	77
Control	100	100	100	100	5	10	13	NA	NA	NA	NA	NA

* meth = methanol; $CaCl_2$ = calcium chloride; IPA = isopropyl alcohol; NA = not available.

† KC1 = U.S.-Army-patented admixture made of 3 weights of sodium nitrate + 1 weight of sodium sulfate.

nol performed even more poorly. However, the methanol protected the mortar from permanent frost damage, allowing full recovery of strength at 56 days. Since methanol retarded strength gain, calcium chloride, a well-known strength-accelerator, was added to see if the results would dramatically improve. They did not. The 2% dosage of calcium chloride produced strengths that were somewhat less than those achieved with the methanol alone, and the 4% dosage produced even lower strengths. Isopropyl alcohol produced results similar to methanol. The strength development of the KC1 mix outperformed the other chemicals. It did not retard strength gain, and it promoted significant strength gain at –5°C and –10°C. None of the chemicals evaluated outperformed the admixture KC1. Therefore, KC1 was used in the subsequent tests to demonstrate the feasibility of using in masonry mortars antifreeze admixtures that were originally developed for concrete.

Setting times

Low temperatures delay the setting times of mortar. This section evaluated the effect of temperature and KC1 on the setting time of mortar.

The experiment was conducted on a type M masonry cement mortar according to ASTM C 403, "Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance." Two mortars were tested: a normal, admixture-free mortar and one that contained 6% KC1 based on cement weight. Both mortars had a moisture content of 16%. Figure 13 presents the setting times as defined in the referenced ASTM standard.

The effect of KC1 on initial and final set of mortar held at room temperature was insignificant. At 5°C (41°F) the KC1 worked better than the control mortar where both initial and final set times were shortened by 4.5 hr. At –5°C (23°F) the initial and final set times for the KC1 mortar were increased by 10 and 18 hr, respectively, compared with the normal mortar held at 5°C. Normal mortar at –5°C froze and could not be measured for set time.

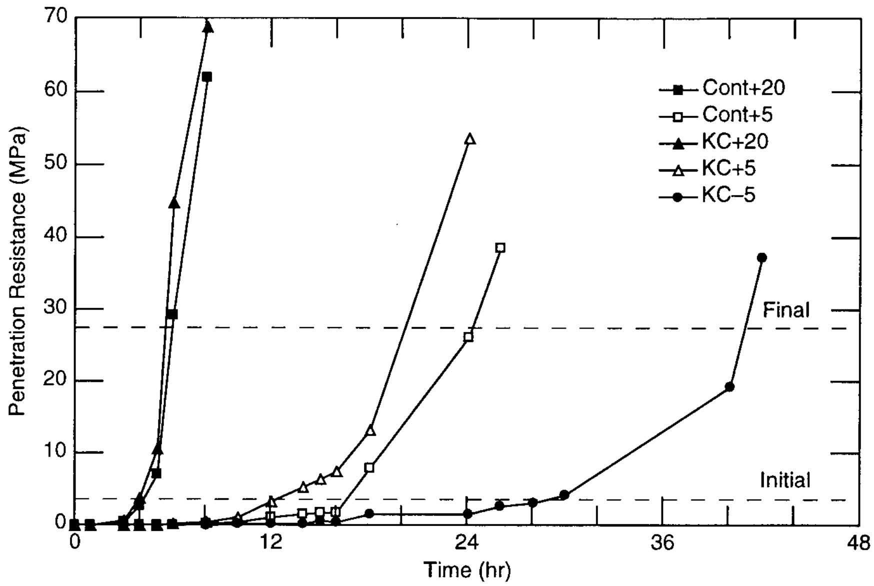


Figure 13. Setting times of admixture-free mortar and mortar containing the admixture KC1.

Effect of KC1 on freeze–thaw resistance

Beam specimens made with type M masonry cement mortar were freeze–thaw tested according to ASTM C 666, procedure B. Two mortars were tested: a conventional, admixture-free mortar and one that contained 6% KC1 based on cement weight. Both mortars had a moisture content of 16%. (Though an air-entraining admixture was not used, a quick examination of the hardened mortar with a microscope showed that both mortars contained entrained air bubbles.) The mechanical condition of each beam prior to and at intervals during the test was monitored by measuring its relative dynamic modulus of elasticity (RDME) according to ASTM C 215. ASTM C 666 considers concrete to be durable if it maintains an RDME above 60% through 300 cycles of freezing and thawing. Since mortar is quite simi-

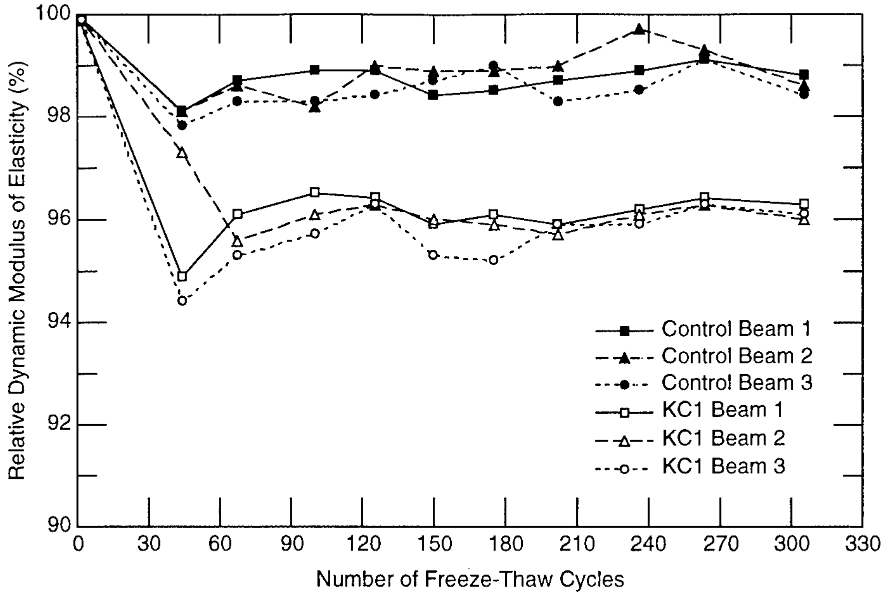


Figure 14. Rapid freeze–thaw (ASTM C 666) test results for specimens with and without KC1.

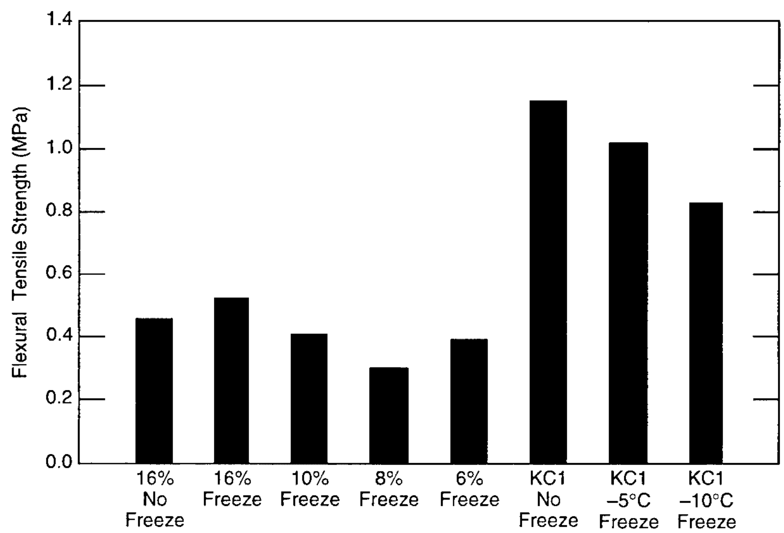


Figure 15. Joint test results of the experiments to assess the effect of KC1 on bond strength, and the effect of mortar moisture content at the time of freezing on bond strength

lar to concrete, these ASTM guides were used to evaluate the mortar beams. Figure 14 shows the test results. As can be seen, both mortars performed well. They had RDMEs at or above 96% at the end of the test. The differences in performance were small enough that it can be concluded that the admixture KC1 did not have a significant effect on the freeze–thaw durability of this mortar.

Effect of KC1 on bond strength

Bond strength of mortar to masonry units is one of the most important engineering properties for unreinforced masonry. The bond strength tests were conducted according to ASTM C 1072, commonly referred to as "the bond wrench test." The test specimens were assemblies of two solid concrete bricks and one mortar joint. The masonry assemblies were tested at an age of 28 days by applying an eccentric compressive load to the assembly resulting in flexural tension across the width of the mortar joint.

These tests evaluated the effect of the admixture KC1 on bond strength. These tests and those

on the effect of mortar moisture content on bond were conducted together, and their results are presented jointly in Figure 15. The results in Figure 15 represent the average of five specimens. Appendix B shows the individual test results. The mortars were made with a type M masonry cement. The KC1 mortars were made with 16% water content, which was the same initial water content as the admixture-free mortars included in Figure 15. The primary finding is that KC1 mortar developed a stronger bond to the masonry units than did normal mortar. This could be due to an increase in the plasticity of the mix, which could have resulted in better mechanical anchoring into the pores of the bricks.

Effect of mortar moisture content at time of freezing on bond strength

This experiment was designed to define the effect of mortar moisture content at the time of freezing (a function of absorption, age, and temperature) on the bond strength of a masonry assembly. The initial moisture content of all mortars was 16%. The moisture content of the mortar at time of freezing was regulated by allowing the masonry assemblies to stand at room temperature until curves like those in Figure 6 indicated that a prescribed moisture content had been achieved. At the prescribed moisture content, the specimens were brought into a –10°C (14°F) room. Twenty-four hours later, the specimens were returned to a 20°C (68°F) room for 28 days. The "bond wrench test" followed. The results presented in Figure 15 represent the average of five specimens (individual test specimen results are included in Appendix B).

Of the sets tested using the control mortar (no admixture), the one with the highest tested bond strength had the highest moisture content: 16%. These prisms were placed into the cold room immediately after construction. These results may be explained by the fact that the mortar in these prisms was in a plastic state when water expansion within the mortar occurred and thus was able to accommodate volume changes. Bond strengths decreased with decreases in mortar moisture content (achieved by longer delay periods between prism construction and placement in the cold room) until a rebound in strength is observed with the estimated 6% mortar moisture. This rebound effect is consistent with mortar compressive strength development as discussed under *Critical Maturity* in the *Freezing Strength* section of this report.

At first glance, these results seem to support current guideline recommendations that mortar be allowed to fall to 6% moisture before it is subjected to freezing. However, it is clear that the 10% moisture content shows the same bond strength as the 6% does. We conclude, from both compression and bond strengths, that mortar can be allowed to freeze at an earlier age than now allowed in current guidelines. The admixtures can lessen cold-weather constraints.

Freeze–thaw durability

Objective

Masonry has historically been viewed as a durable construction material. Long-term performance of concrete masonry structures exposed to the weather in cold regions requires the use of units that can resist the potentially destructive forces imposed on the units by cyclical freezing and thawing. The severity of the exposure and the properties of the masonry unit control the long-term performance of the units.

The objective was to evaluate several test methods that could be used as indicators of the freeze–thaw durability of concrete masonry units. Two freeze–thaw test methods that subject water-saturated specimens to cyclical freezing and thawing were considered: ASTM C 666, "Resistance of Concrete to Rapid Freezing and Thawing," and ASTM C 1262, "Method for Evaluating the Freeze–Thaw Durability of Manufactured Concrete Masonry Units and Related Units." The first of the two methods was originally developed for structural concrete, and the second is a new method that was developed specifically to evaluate dry mix, no-slump concrete products such as concrete masonry units.

Knowledge about the air void structures of other related materials has provided insight into freeze–thaw durability performance. Therefore, two other test methods were also considered to determine if they might provide similar insights into concrete masonry unit durability: ASTM C 457, "Microscopic Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete," and ASTM D 4404, "Determination of Pore Volume Distribution of Rock and Soil by Mercury Intrusion Porosimetry."

To evaluate these methods, six different sets of concrete segmental retaining wall units were used. The units are manufactured using the same materials and methods as conventional concrete masonry units.

Rapid freeze–thaw test for concrete, ASTM C 666

At the time this project was initiated, there was no standard method designed specifically to evaluate the freeze–thaw resistance of concrete masonry units (Method C 1262 was not approved by ASTM until late 1994). Before then, ASTM C 666 was often used for this purpose when needed. The ASTM C 666 test method includes two different procedures: procedure A, Rapid Freezing and Thawing in Water, and procedure B, Rapid Freezing in Air and Thawing in Water. Both procedures are considered to be more severe than field conditions, primarily due to the rapid freezing rates in the test of roughly 5 to 15°C (9 to 27°F)/hr as compared with common field rates of less than 3°C (5.4°F)/hr. As with all laboratory freeze–thaw test methods, the test is not intended to simulate field conditions, but instead it produces an indication of relative freeze–thaw resistance between different specimens.

Test specimens were saw-cut from units representing each of the six different sets of segmental retaining wall units. Due to the size limitations of the full-size units, the saw-cut test specimens were much smaller than required by C 666. The specimens were subjected to cyclical freezing and thawing using procedure B. Prior to testing and at regular intervals, the specimens were removed from the test chamber to evaluate their condition using ASTM C 215, "Test Method for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens." The results of this method are expressed as a percentage of the original relative dynamic modulus of elasticity (RDME). Each specimen starts with an RDME of 100, but this value decreases throughout the duration of the C 666 test as the internal structure of the specimen is damaged by the expansive forces of the water within its pores.

The conventional criterion used with structural concrete is that specimens must retain at least 60% of the original RDME at the end of 300 freeze–thaw cycles. If this criterion were used to evaluate the six sets of segmental retaining wall units, all would be considered to fail. However, it is important to note that the criterion used to evaluate performance of structural concrete used in horizontal highway applications would not be appropriate for use in evaluating concrete masonry units. Freeze–thaw damage requires saturation of the concrete. Vertical, free-draining concrete masonry walls are rarely saturated. Therefore, their exposure conditions are much less severe than those of horizontal structural concrete, and the criteria for evaluating satisfactory performance in the test method should not be consistent for the two materials. While retaining walls may have a somewhat greater saturation potential than most concrete masonry walls, their exposure is still much less severe than most highway concrete.

The results of the tests cannot be compared to standard pass–fail criteria, since none exists for concrete masonry units. However, the results (shown in Figure 16) do provide useful information by demonstrating the relative performance between the specimens.

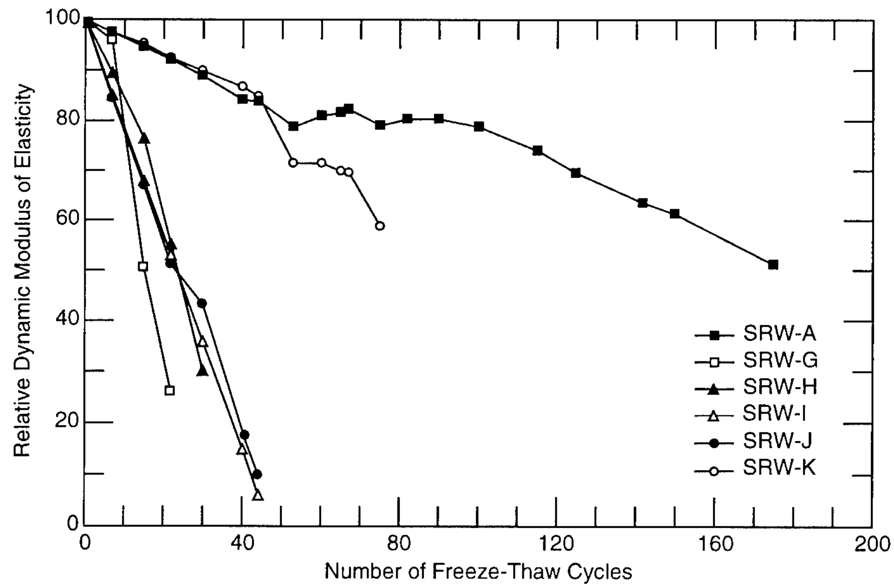


Figure 16. Results of the modified ASTM C 666 freeze–thaw test on segmental retaining wall (SRW) units.

New freeze–thaw test method for concrete masonry units, ASTM C 1262

As part of this research effort, a new test method was developed specifically to evaluate the freeze–thaw durability of concrete masonry units. This method was presented to the American Society of Testing and Materials (ASTM) and was first published in 1994 as ASTM C 1262. Test specimens are partially submerged in water and sealed in flexible containers. Air temperatures around the containers are controlled for thaw cycles at 20°C (68°F) and for freeze cycles at –15°C (5°F). The method was written specifically to accommodate automatically cycling freeze–thaw chambers to perform up to three cycles per day as well as for conventional freezers. Performance of specimens throughout the test is determined by weight loss. Residue within the containers, the result of surface scaling and general breakdown of the test specimen, is collected and reported as a percentage of the original weight of the specimen. A copy of the method is included in Appendix C.

Due to the limited experience with this method, there are no standard freeze–thaw durability requirements for concrete masonry units using this method as well. Once again, however, the method permits a comparison between the performance of the different sets of units evaluated. For reference purposes, the compressive strength, absorption, and unit weight of the concrete used in these units were also determined. These values, measured in accordance with ASTM C 140, have often been used in the past, with mixed results, to ensure field performance in freeze–thaw environments.

Table 8 summarizes the data gathered during this test. As can be seen, SRW A was clearly most durable. It withstood an estimated 1500 cycles of freezing and thawing compared with less than 200 cycles for all the others. Figure 17 presents the

Table 8. Average tested properties of SRW units using ASTM C 1262 and C 141.

*Specimen SRW**	*No. of cycles at 1% wt loss*	*Compressive strength (MPa [psi])*	*Unit weight (kg/m³ [lb/ft³])*	*Absorption (kg/m³ [lb/ft³])*
A	1500†	43.8 (6351)	2138 (133.5)	98 (6.1)
G	90	52.9 (7669)	2233 (139.4)	87 (5.4)
H	180	68.9 (10,283)	2310 (144.2)	69 (4.3)
I	55	26.6 (3860)	1757 (109.7)	170 (10.6)
J	50	30.9 (4474)	1720 (107.4)	232 (14.5)
K	60	29.4 (4268)	1607 (100.3)	157 (9.8)

* SRW = Segmental retaining wall unit.

† Estimated value. Test was terminated at 875 cycles with average weight loss of less than 0.5%.

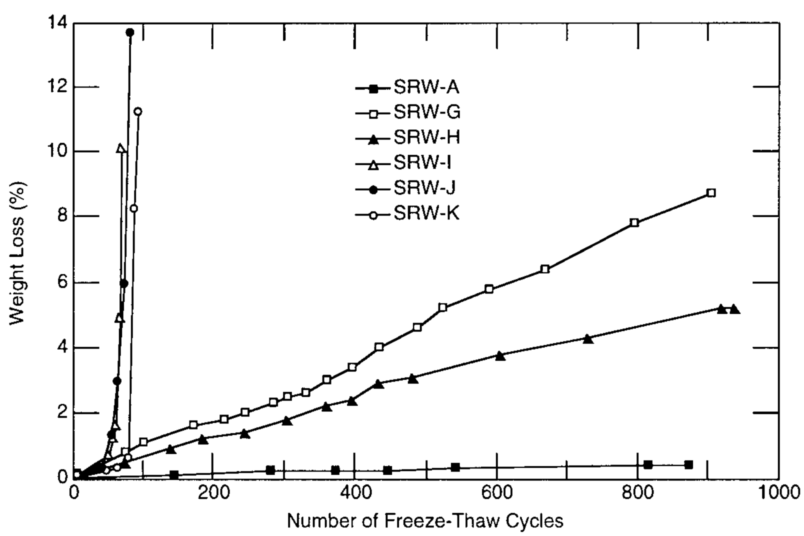


Figure 17. Freeze–thaw test results for median specimen from each set of segmental retaining wall units (ASTM C 1262).

results in graphical form. Appendix D presents individual results from each sample tested.

Microscopic examination of the air void system

A test method used to assess the susceptibility of porous materials to freezing and thawing is ASTM C 457, "Standard Practice for Microscopical Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete." Although this test method was developed for concrete, its principles may be used for other concrete-like materials. The specimens are saw-cut slabs that are ground and polished and then observed through a stereo microscope. The main parameters of the test are the air content and the spacing factor, an indication of the distance within the cement paste that moisture must travel to reach an unsaturated void to release hydraulic pressure during freezing. The test examines the air-void parameters of the cement paste but fails to include the characteristics of the aggregate. The test is carried out under the assumption that the aggregate is freeze–thaw-durable. Experience gained with structural concrete indicates that this test can reasonably predict freeze–thaw susceptibility if the aggregate phase is freeze–thaw resistant.

The most significant parameters shown in Table 9 are the spacing factor and the air content. (Detailed information is provided in Appendix E.) A small spacing factor is an indicator of durable material. Spacing factors of less than 200 μm indicate good freeze–thaw resistance in concrete, spacing factors above 250 μm indicate frost susceptibility, and values in between constitute a gray area. As explained above, this test method is concerned with the cement paste only. It ignores the characteristics of the aggregate. Although not included in the standard test method, a brief description of the aggregates used in the manufacture of each set of specimens is included in Table 9 for reference.

Mercury intrusion porosimetry

Mercury intrusion porosimetry (MIP) is a newer technique that determines the pore size distribution in porous materials such as rock, concrete, and mortar. Its use with masonry is still a subject of research. Samples from the specimens that were freeze–thaw-tested as described above were also tested by mercury intrusion porosimetry. Small samples were enclosed in a small test chamber capable of withstanding high pressures. Mercury was injected into the chamber to fill the air space available. Higher pressures are needed to intrude mercury into smaller pores. The pressure was increased gradually and the amount of mercury that went into the chamber was recorded. The pressure needed to intrude mercury was correlated to the pore size by means of the Washburn equation (Washburn 1921). The amount of mercury intruded at a given pressure range was correlated to the total pore volume of a given pore size. The procedure for this test is described in ASTM D 4404, "Standard Test Method for Determination of Pore Volume and Pore Volume Distribution of Rock and Soil by Mercury Intrusion Porosimetry."

Based on the documented mechanisms of freezing of moisture in the pores of cement paste, pore sizes can be classified in three ranges:

1) Protective pores, larger than 5 μm
2) Capillary pores, from about 0.1 μm to 5 μm
3) Subcapillary pores smaller than 0.1 μm.

Protective pores are usually benign because they provide reservoirs for excess moisture to migrate to during freezing, thereby relieving hydraulic pressure. Moisture in these voids can freeze, but the voids are usually water-free because neighboring capillary pores draw their moisture away by suction. Capillary pores are small enough to generate high suction, which fills them up, and large enough that the moisture in

Table 9. Test results from the microscopic examination of hardened mortar.

*Specimen SRW**	*Volume fractions (%) Aggregate*	*Paste*	*Air*	*Spacing factor (μm)*	*Aggregate description*
A	52.6	31.0	16.4	143	Quartzite, sound
G	67.8	22.6	9.6	137	Sound, well graded, angular
H	67.3	28.2	4.5	212	Sound, well graded, angular
I	54.6	32.2	13.2	133	Coarse pores
J	60.2	32.2	7.6	271	Mostly porous and soft
K	51.9	35.2	12.9	106	Pumice with coarse vesicles

* SRW = Segmented retaining wall unit.

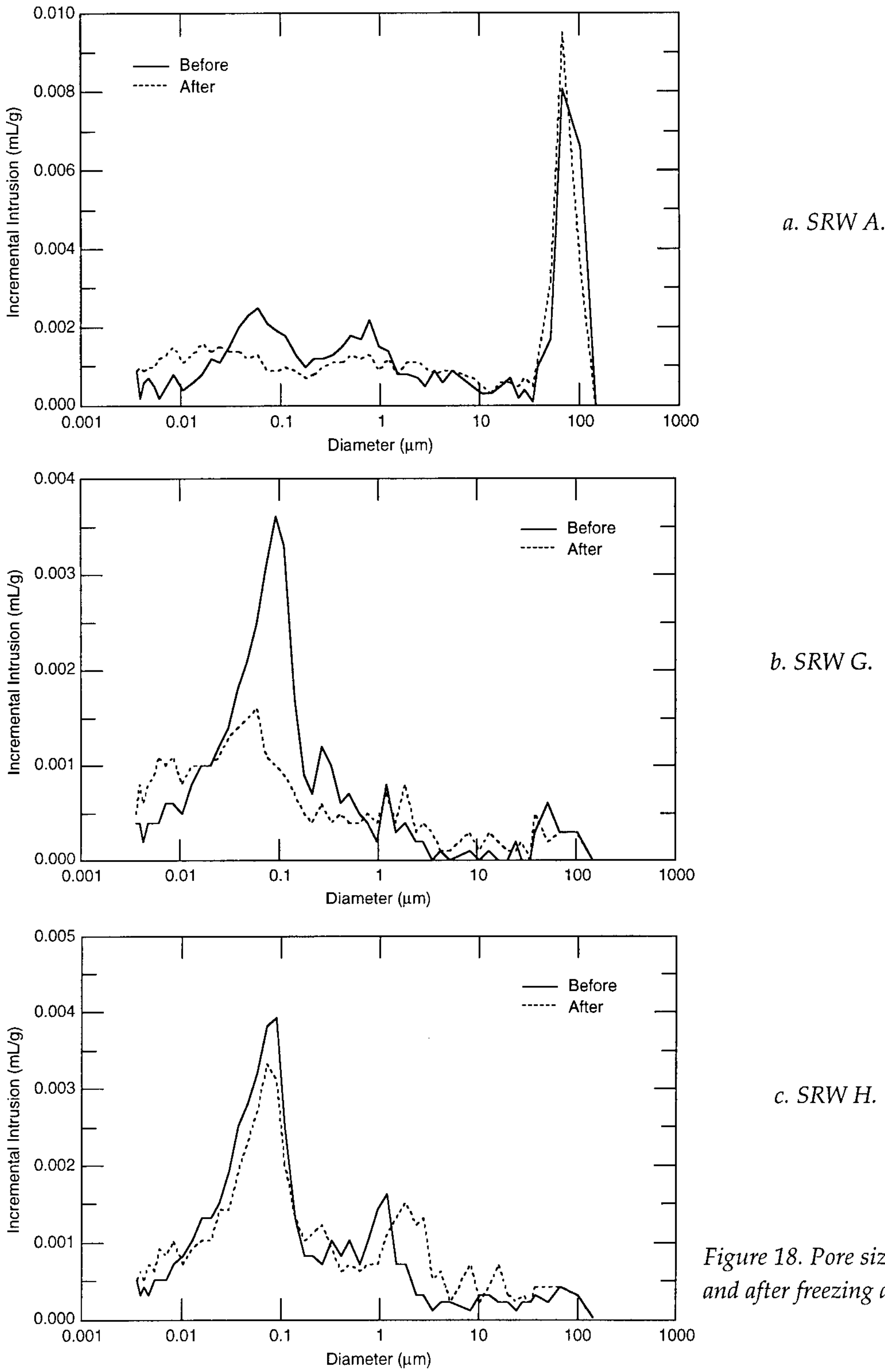
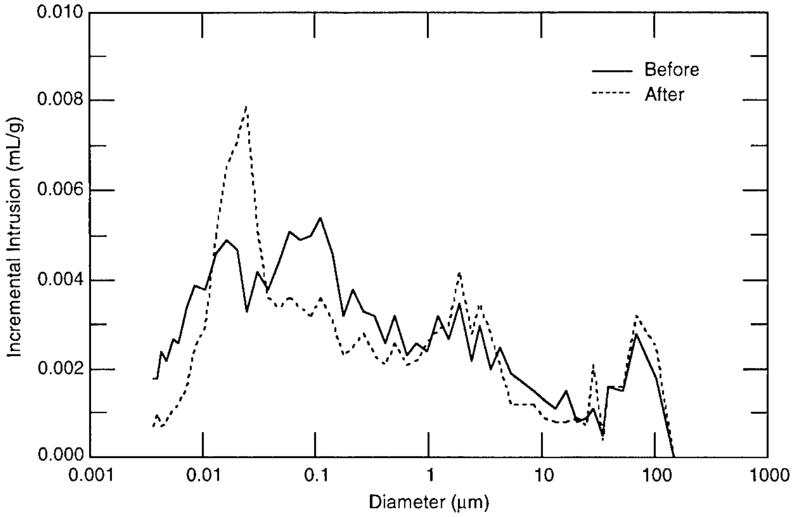


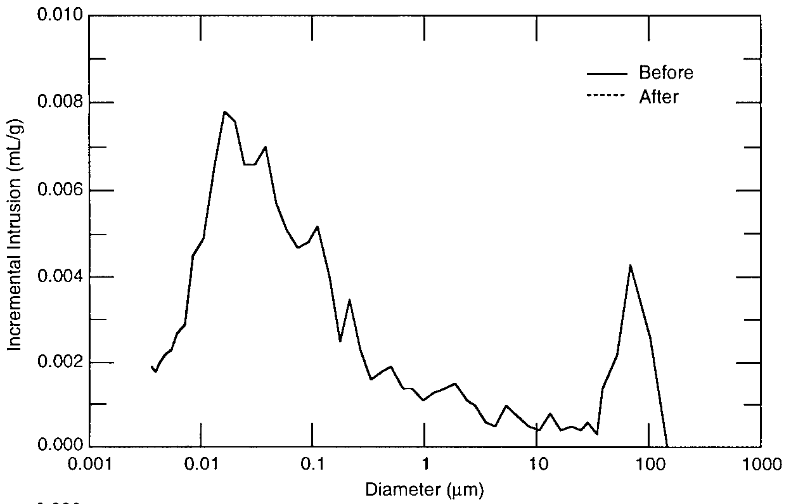
Figure 18. Pore size distributions before and after freezing and thawing.

them freezes at common low temperatures. Subcapillary pores also have very high suction properties that keep them filled with moisture, but due to the small sizes of these pores the moisture within them is maintained in a supercooled condition without freezing.

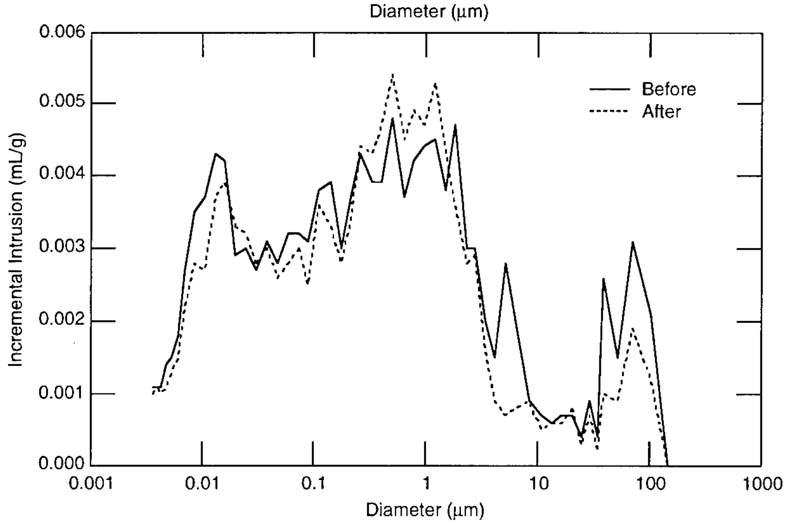
Figure 18 shows the test results from the mercury intrusion porosimetry (MIP) test. The tests were conducted in replicate specimens before and after 300 ASTM C 666 freeze–thaw cycles. There were two objectives in using this MIP test. The first was to see if there may be a reasonable correlation between pore size distribution in concrete masonry units and freeze–thaw test results.



d. SRW I.



e. SRW J.



f. SRW K.

Figure 18 (cont'd). Pore size distributions before and after freezing and thawing.

The second objective was to determine if this method would detect changes in the pore size distribution of the test specimen due to freezing and thawing action.

Based on these results, MIP tests performed before and after freeze–thaw cycling do not show the expected increases in pore size. Comparisons between the results of these tests and the other test methods are summarized in the next section of this report.

Comparison of test results

Table 10 compares the results of the different test methods for six sets of test specimens classi-

Table 10. Relative performance of specimens in each test.

SRW set	*ASTM C 666*	*ASTM C 1262*	*ASTM C 457*	*ASTM D 4414*
A	Excellent	Excellent	Good	Good
G	Poor	Fair	Good	Fair
H	Poor	Good	Fair	Fair
I	Poor	Poor	Good	Poor
J	Poor	Poor	Poor	Good
K	Good	Poor	Excellent	Poor

fied in one of four categories: excellent, good, fair, and poor. These ratings are not defined in any of the referenced methods. They are used simply for the purposes of this report to evaluate potential correlation between the results.

In general, the two freeze–thaw test methods used, C 666 and C 1262, provided fairly similar results in identifying the relative performance of the sets of units, with several notable exceptions. For example, both methods indicated that set A was clearly the most durable of all sets evaluated, and both methods demonstrated similarly poor performances for sets I and J. However, the results contrasted regarding the remaining sets G, H, and K. Method C 666 indicated that sets G and H performed worse than sets I and J and that set K performed well. These results are nearly opposite to those of Method C 1262, which showed G and H to be good performers and set K to be a poor performer similar to that of I and J.

The microscopic examination and MIP (C 457 and D 4404, respectively) results for sets A, G, and H demonstrated some promise as a method of predicting freeze–thaw performance using one of the test methods. The same was not the case for sets I, J, and K. However, the less durable aggregates used in each of these last three sets may have resulted in the poor correlation between test methods, since the microscopic examination and MIP can only evaluate the paste structure. The microscopic examinations can often give indications of the soundness of the aggregate, however. Potentially frost-susceptible aggregates were identified in examinations of specimens from sets I, J, and K.

With the limited data available here, it appears that Method C 1262 may be a better method for evaluating freeze–thaw durability of these concrete masonry related units. The C 1262 results show better differentiation between sets of units. The C 1262 test results compare better with the results of microscopic evaluations and mercury intrusion porosimetry. Both methods are time-consuming and expensive to perform, but equipment costs are less for the C 1262 method, and some laboratories are equipped to perform it. Due to the cost and time needed to perform these tests, additional future consideration should be given to the use of microscopic evaluations, MIP, and other methods of providing indicators of potential unit durability.

FIELD DEMONSTRATION

Objective

A concrete masonry wall consisting of $25^1/_2$ blocks per row that was five blocks high was constructed in northern Michigan at the U.S. Army Corps of Engineers Soo Locks, Sault Ste. Marie, in March 1995. Each block was nominally 203 × 203 × 406 mm (8 × 8 × 16 in.). The objectives of this experiment were to demonstrate the practicality of using antifreeze admixtures in masonry mortar and to compare it with conventional cold-weather masonry practices.

Temporary enclosure

A temporary enclosure was erected in which the wall was constructed. Half of the shelter was heated and half was unheated. A canvas separated the two halves. Conventional type M masonry cement mortar was used to build the section of wall within the heated portion of the shelter, while the same type of mortar with the addition of an antifreeze admixture was used to build the section of wall within the unheated section of the shelter.

The mortar

All mortar used for building the wall was hand-mixed with hoes in a mixing trough in the heated side of the shelter. The ingredients, which were all preheated to the temperature of the enclosure, were preweighed and combined in the proportions shown in Table 1. The antifreeze admixture KC1 was dissolved in a portion of mixing water. The sand and cement were thoroughly combined before water was added. The amount of water added was estimated by eye by the mason until a desired consistency was achieved. The mortar was retempered as needed. The average water contents of the as-mixed mortars were 12.9 and 13.4% for the conventional and the antifreeze mortar, respectively.

Constructing the wall

Both wall sections were laid in running bond with faceshell mortar bedding using conventional

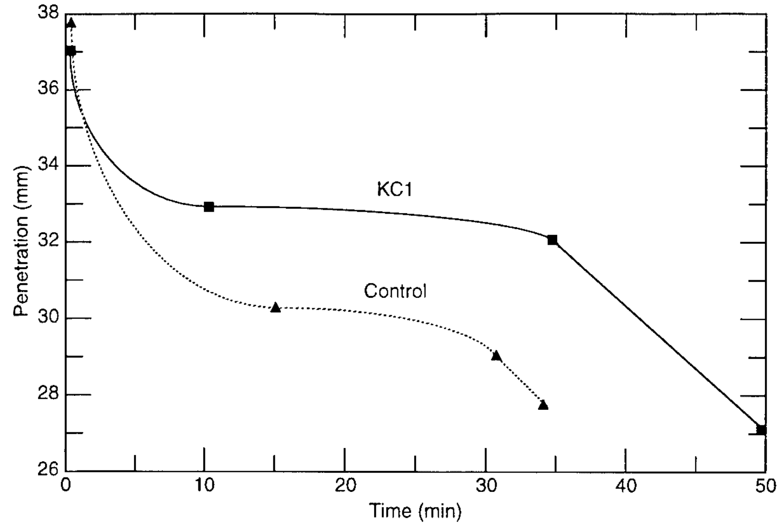


Figure 19. Penetration of mortar with and without the antifreeze admixture.

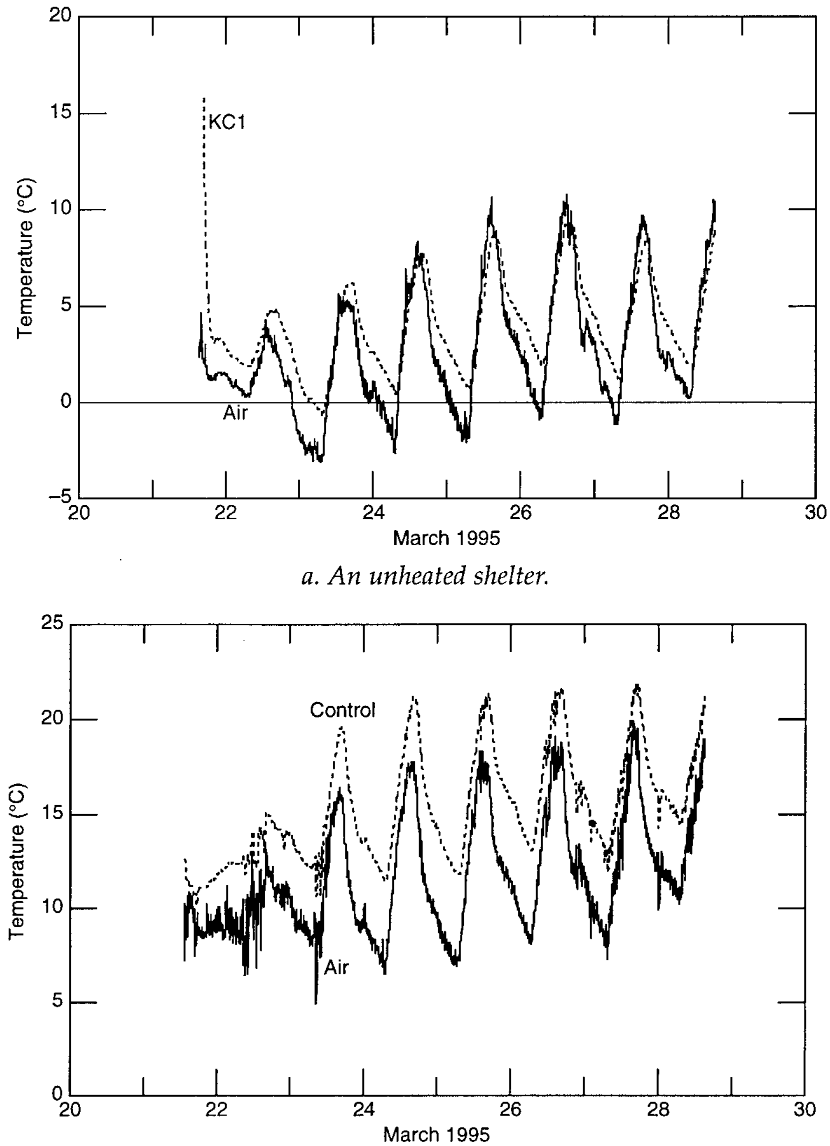
Figure 20. Building the wall.

masonry construction techniques. The mortar was tooled concave when it was thumbprint hard. The masons found that the admixtured mortar adhered very well to the masonry units and that it remained workable much longer than did the conventional mortar; this was probably due to the differences in air temperature. Figure 19 compares the average penetration of the three conventional mortars (on the warm side) to the average penetration of the three admixtured mortars (on the cold side) over time. Due to the lower-than-average initial mixing moisture content, the cone penetrations for the fresh mortar averaged about 38 mm (1.5 in.). The masons retempered the mortar when its penetration dropped to about 28 mm (1.1 in.). The three batches of conventional mortar were each retempered once, but the two antifreeze mortar batches were not retempered.

For construction of the wall section (Fig. 20) on the cold side, masonry units were transferred from the heated enclosure and used immediately. The mortar made with KC1, once mixed, was placed in the cold side and used within about 50 min.

Thermal history

Mortar and air temperatures were recorded every 5 minutes for seven days. Thermocouples in each side of the shelter monitored temperatures in the mortar beds between masonry units, in 5 × 10 cm (2 × 4 in.) mortar cylinders, and in the air next to the walls. The temperature of the mortar cylinders, which were stored adjacent to the wall sections, was nearly identical to that in the



a. An unheated shelter.

b. A heated shelter.

Figure 21. Thermal history of the masonry walls and surrounding air.

mortar joints. Figure 21 shows the 7-day temperature history of the cylinders and air in each side of the shelter. The initial mortar mixture temperatures were approximately 17°C (62°F) for both conventional and antifreeze mortars. While typical protection methods for newly constructed concrete masonry may include overnight heated enclosures, the heated wall section for this project was protected for a full 7 days. The mortar on the unheated side of the shelter had a 7-day average temperature of 3.9°C (39°F), a maximum temperature of 9.5°C (49°F) at 3:30 p.m. on the 26th, and a minimum of –0.6°C (31°F) at 7:30 a.m. on the 23rd. In contrast, the mortar on the heated side of the shelter had a 7-day average temperature of 15.3°C (60°F), a maximum of 22°C (71.6°F) at 5:15 p.m. on the 27th, and a minimum of 10.1°C (50°F) at 5:15 p.m. on the 21st.

Mortar strength

Two sets of 50- × 100-mm (2- × 4-in.) cylindrical samples were cast from each type of mortar. The samples made from the conventional mortar were stored in the warm side of the shelter, and those from the antifreeze mortar were stored in the cold side. The cylinders were allowed to cure in their respective environments for 7 days. Then they were shipped to CRREL, stored at room temperature, and tested at a maturity of 28 days. The strength results are presented in Figure 22. The

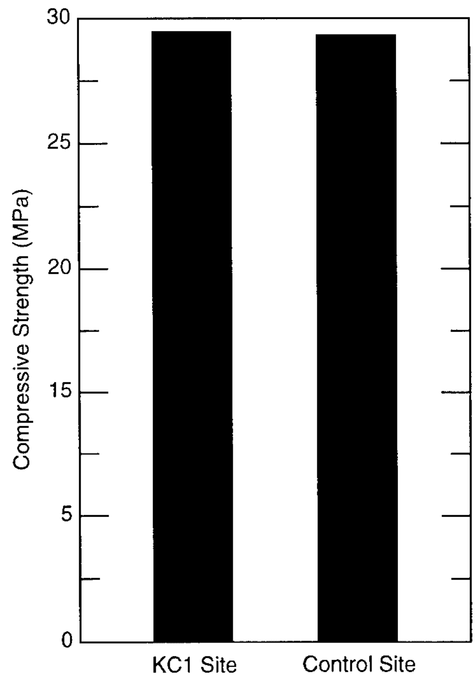


Figure 22. Strength of mortar cylinders cast during construction.

antifreeze mortar, cured in the unheated side of the shelter for 7 days, is as strong as the conventional mortar.

Efflorescence

Efflorescence is of concern whenever anything is added to the mortar, and it appears to occur with greater frequency in cold-weather construction projects. It was reported that the wall exhibited some white discoloring at the joints on the half of the wall containing the KC1 admixture during the spring time. However, after the first rain the white coloring had disappeared. During a summertime inspection, both halves of the wall appeared identical.

Cost comparison

The primary difference between conventional winter masonry construction and masonry construction done with antifreeze admixtures is with the type of freeze protection provided in each case. The conventional practice is to provide heat to keep the masonry above freezing until it gains sufficient strength. With antifreeze admixtures, the mortar is placed and cured in the cold without heaters or insulation. However, since the work environment must not be too cold for the workers, most winter masonry construction projects would require a temporary shelter regardless of which construction method is employed. The primary difference between the two methods is that with the antifreeze method the shelter would not have to be heated after the work stopped. In this case, the weather was mild enough that the antifreeze side of the shelter did not have to be heated for the comfort of the masons. The workers were able to stay warm just by wearing jackets but no gloves. There was no significant difference in the production rate between the two walls. Other labor and materials are considered common to both construction methods.

A heater produced 34,000 Btu/hr for each day it was in operation. Two heaters were used. A commonly used heat source on construction sites is liquid propane. At $0.94/gal and 91,000 Btu/gal, the cost to keep the conventional mortar above freezing was about $15/day. On the other hand, based on costs for other admixtures sold on the market today, the antifreeze admixture is estimated to cost about $15.00 for the total amount of admixture used on this project. Since the mortar only had to be heated for 1 day, the antifreeze admixture produced no cost saving—it cost as much as the heat. Keep in mind that the average daily outdoor temperature was roughly 3°C (37°F). Colder temperatures would increase heating demand. The saving in this case, however, is that no fuel had to be burned to protect the antifreeze mortar.

Although the cost comparison and productivity of the two walls in this demonstration did not yield significant differences, antifreeze admixtures may cause significant savings for masonry built with large, prefabricated units. In this type of construction, cranes are used to lift and place the heavy units into the assembly, and the ability to do this work in the open, without a shelter, opens new opportunities for cost-effective winter masonry construction.

CONCLUSIONS

1. The frost susceptibility of newly placed mortar is directly related to its moisture content. Fresh mortar is frost-susceptible because it is water-saturated. Dry mortar is frost-immune. After mortar is placed, its moisture content decreases. There is a critical moisture content at which the mortar becomes frost-resistant. The experiments in this project showed that the moisture content of the masonry units at the time of assembly and the absorptive characteristics of the unit are the pre-

dominant factors that determine the rate of mortar moisture loss. The air temperature and the temperatures of the masonry units and the mortar had only a minor effect on the rate of moisture loss from mortar.

2. Mortar becomes immune to a single cycle of freezing at a moisture content between 8 and 10%.
3. The time for mortar to reach a moisture content of 8% is typically about 4 hours.
4. Mortar cured at or above 5°C (41°F) reaches critical maturity within 6 hours. Critical maturity is the minimum maturity needed for mortar to withstand one event of freezing without damage.
5. Freezing does not always harm early-age mortar. The 7-day strength of mortar can be increased by around 10% when it is frozen after about 10 to 16 hours of curing at or above 5°C, provided that the time in freezing temperatures is discounted from the computation of the 7 days.
6. Current guidance allows mortar to be heated up to 50°C (120°F). This study showed that 40°C (104°F) mortar placed in the cold does not stay above freezing appreciably longer than 5°C (41°F) mortar. Therefore, there is minimal benefit from heating mortar above 20°C (68°F). Thin mortar joints will not remain above freezing significantly longer when higher temperatures are used.
7. Current guidance requires that mortar be thermally protected for a minimum of 16 hours. Based on critical moisture contents and critical maturities, thermal protection could be realistically reduced to 4 to 6 hours. A conservative change to current practice would be to relax the time of thermal protection from the current 16 hours to 8 hours.
8. Antifreeze admixtures are a viable alternative to thermal protection. A major drawback is that, at the present time, no antifreeze admixture commercially available is labeled for use with concrete or with masonry. However, the ingredients of the U.S.-Army-patented antifreeze admixture KC1 are available as generic chemicals from various sources. The recommended dosage is 4.5% of sodium nitrate and 1.5% of sodium sulfate by weight of portland cement. These chemical compounds are usually supplied in powder form and dissolve easily into the mix water. Other antifreeze admixtures for concrete or masonry may become commercially available in the future.
9. The laboratory tests showed that the antifreeze admixture KC1 had a negligible effect on the freeze–thaw durability of mortar. This admixture decreased the setting times at low temperature and substantially increased the bond between mortar and the units.
10. Although parameters such as spacing factor, specific surface, number of air voids per 25 mm (1 in.), total air content, and pore size distribution are used frequently to predict freeze–thaw durability of slumpable concrete, these parameters are less reliable when it comes to dry-cast concrete performance as measured by ASTM C 666 (procedure B) or ASTM C 1262.
11. Although C 666 uses change in relative dynamic modulus of elasticity (RDME) to measure freeze–thaw durability performance, cumulative percent weight loss per surface area as used in C 1262 may be a more appropriate measure of performance for dry-cast concrete specimens. More study is needed.
12. No physical property measured in this study, including compressive strength, density, or absorption, consistently predicted the same freeze–thaw resistance of dry-cast concrete products as that measured using C 666 or C 1262.
13. The cost comparison and productivity of the two walls built as a demonstration in this project did not yield significant cost differences when the outdoor air temperature averaged 3°C (37°F). Colder weather will increase heating demand. However, in all cases where some heating is required, use of antifreeze admixtures will reduce the amount of fuel burned for thermal protection.

RECOMMENDATIONS

1. The laboratory experiments in this project showed that the time of thermal protection for masonry may safely be reduced from the current 16 hours to 8 hours if the following conditions are met:
   a) The masonry units are not extremely damp. If this is suspected, the units must be allowed to dry at room temperature until all visible signs of moisture disappear.

b) The masonry units are cold. However, if units are below 5°C (41°F), they must be allowed to warm up in a heated shelter.

2. Increased thermal protection is required for masonry constructed using wet masonry units. Therefore, it is recommended that masonry units delivered to the job site be protected from moisture as much as possible. Units that are visibly damp should not be laid. It is generally not considered necessary to dry wet units by heat. Air drying is typically sufficient, provided units are unstacked and separated to permit air flow between them.
3. The practice of heating the mortar ingredients prior to mixing to temperatures greater than 5°C does not provide significant thermal protection. In addition, very high water temperatures may cause flash set. Therefore, it is recommended that the mortar mix be produced at temperatures of 5 to 20°C (41 to 68°F).
4. Antifreeze admixtures originally developed for concrete provide enhanced performance to masonry mortar. The experiments conducted in this project support a recommendation for their use in masonry mortars as soon as they become commercially available.

COMMERCIALIZATION AND TECHNOLOGY TRANSFER

The knowledge derived from this research is being shared with the engineering community through conference papers, technical reports, updates to guide specifications, and new testing methods:

- A conference paper was presented at the American Society of Civil Engineers 8th International Specialty Conference on Cold Regions Engineering in Fairbanks, Alaska, in August of 1996. The paper was published in the proceedings of this conference.
- A proposal (Appendix F) was submitted to the International Masonry Industry All Weather Council to update the minimum thermal protection requirements included in the Council's guide specifications. The proposal was submitted through NCMA, which is a member of that council.
- A new standard test method was developed and adopted by ASTM under specification C 1262, "Standard Test Method for Evaluating the Freeze–Thaw Durability of Manufactured Concrete Masonry Units and Related Concrete Units." This new standard has been published in the ASTM Annual Book of Standards.

This study showed that antifreeze admixtures can promote appreciable strength in mortar when its internal temperature is below 0°C (32°F). However, these products are yet to become commercially available.

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APPENDIX A: ABSORPTION TEST RESULTS

Table A1. Summary of water uptake test results.

Test no.	*Unit type*	*Unit no.*	*Unit surface*	*Unit temp. (°C)*	*Unit moisture*	*Water temp. (°C)*	*Air temp. (°C)*	*Weight increase (g) of unit (at specified time in min.)* 0	1	2	5	10	15	30	60
1	CMU A	1	Top	20	Dry	20	20	0	159	186	209	227	231	245	254
		1	Bottom					0	163	191	213	231	245	259	272
		2	Top					0	73	86	109	132	141	159	177
		2	Bottom					0	68	82	95	113	122	141	163
Surface area															
Top = 375 cm^2			Average of top surfaces from both units...					0	116	136	159	179	186	202	215
Bottom = 428 cm^2			Average of bottom surfaces from both units ...					0	116	136	154	172	184	200	218
			Average of all surfaces from both units ...					0	116	136	156	176	185	201	217
2	CMU B	1	Top	20	Dry	20	20	0	91	122	168	222	254	327	390
		1	Bottom					0	240	304	386	435	458	494	531
		2	Top					0	91	127	177	227	259	322	395
		2	Bottom					0	268	331	417	472	503	558	617
Surface area															
Top = 375 cm^2			Average of top surfaces from both units...					0	91	125	172	225	256	324	392
Bottom = 428 cm^2			Average of bottom surfaces from both units ...					0	254	318	401	454	481	526	574
			Average of all surfaces from both units ...					0	172	221	287	339	369	425	483
3	CMU C	1	Top	20	Dry	20	20	0	77	91	109	127	141	163	191
		1	Bottom					0	150	168	195	213	227	254	277
		2	Top					0	45	54	73	86	95	118	141
		2	Bottom					0	168	181	209	222	236	259	281
Surface area															
Top = 375 cm^2			Average of top surfaces from both units...					0	61	73	91	107	118	141	166
Bottom = 428 cm^2			Average of bottom surfaces from both units ...					0	159	175	202	218	231	256	279
			Average of all surfaces from both units ...					0	110	124	146	162	175	198	222
4	Brick	1	Side	20	Dry	20	20	0	62	66	67	69	70	74	76
		2	Side					0	51	53	55	57	58	61	64
		3	Side					0	56	58	60	62	64	66	68
Surface area = 172 cm^2			Average of all three units ...					0	56	59	61	63	64	67	69
5	Brick	1	Side	20	Normal	20	20	0	29	30	31	32	33	—	—
		2	Side					0	30	32	33	34	34	—	—
		3	Side					0	34	34	37	37	38	—	—
			Average of all three units ...					0	31	32	33	34	35	—	—
6	Brick	1	Side	20	Wet	20	20	0	35	40	43	46	46	—	—
		2	Side					0	26	28	30	31	32	—	—
		3	Side					0	30	34	37	38	40	—	—
			Average of all three units ...					0	30	34	37	38	39	—	—
7	Brick	1	Side	5	Dry	5	5	0	65	67	70	71	73	76	—
		2	Side					0	52	55	57	60	60	62	—
		3	Side					0	57	62	64	67	68	68	—
			Average of all three units ...					0	58	62	64	66	67	69	—
8	Brick	1	Side	5	Dry	20	5	0	70	75	76	78	79	81	—
		2	Side					0	60	64	66	68	69	71	—
		3	Side					0	53	56	58	61	61	64	—
			Average of all three units ...					0	61	65	67	69	70	72	—
9	Brick	1	Side	5	Dry	30	5	0	52	55	57	58	60	62	—
		2	Side					0	47	51	53	55	57	61	—
		3	Side					0	70	71	73	75	76	80	—
			Average of all three units ...					0	57	59	61	63	64	68	—

Table A2. Summary of mortar absorption test results.

Test no.	Unit type	Unit temp (°C)	Unit moisture	Mortar type	Mortar temp. (°C)	Air temp. (°C)	Mortar properties Air	Mortar properties Unit wt.	Flow	Penetr.	Mix water (%)	Mortar moisture content (at specified time in min.) 0	5	15	30	45	60	120	240	1440	Min. to 6%
1	Brick	20	Dry	MC-M	20	20	9.3	125.5	131.0	65.0	14.8	15.4	12.3	11.3	9.6	9.2	7.8	6.5	3.4	1.7	140
2	Brick	20	Dry	MC-S	20	20															
3	Brick	20	Dry	MC-N	20	20	8.6	125.9	131.0	62.0	15.1	15.1	11.8	11.5	9.6	8.4	7.5	6.3	3.4	1.0	133
4	Brick	20	Dry	PCL-M	20	20	3.1	133.6	131.0	59.0	21.0	15.2	14.0	11.3	9.7	8.8	8.1	5.2	3.7	0.6	105
5	Brick	20	Dry	PCL-S	20	20															
6	Brick	20	Dry	PCL-N	20	20	1.9	128.7	126.0	56.0	24.3	19.0	16.0	14.3	12.9	11.1	10.1	7.8	5.0	1.7	198
7	Brick	20	Dry	MC-M	5	5	10.6	123.7	134.0	69.0	14.8	14.8	12.1	10.8	9.1	8.6	7.5	6.5	4.8	2.0	160
8	Brick	20	Dry	MC-M	20	5	10.2	124.3	133.0	66.0	14.8	15.9	11.8	10.4	8.6	8.0	7.4	6.1	3.5	1.2	125
9	Brick	20	Dry	MC-M	30	5	10.0	124.6	131.0	63.0	14.8	13.9	10.5	9.8	7.9	7.5	5.3	5.1	3.7	1.5	55
10	Brick	5	Dry	MC-M	5	5	10.8	123.5	133.0	69.0	14.8	14.6	11.9	11.5	10.0	9.0	8.1	6.0	5.0	1.1	120
11	Brick	5	Dry	MC-M	20	5	10.0	124.6	131.0	66.0	14.8	14.5	12.4	10.9	9.5	9.2	8.0	6.2	4.6	0.8	136
12	Brick	5	Dry	MC-M	30	5	9.7	125.0	131.0	59.0	14.8	14.1	12.2	10.9	10.2	9.9	8.9	7.3	5.0	1.3	188
13	Brick	20	Normal	MC-M	5	5	10.6	123.8	135.0	66.0	14.8	15.4	13.0	11.5	10.8	10.7	9.9	8.8	6.9	3.0	516
14	Brick	20	Normal	MC-M	20	5	9.9	124.7	133.0	63.0	14.8	14.4	13.0	11.9	11.7	10.7	10.4	10.1	9.1	7.6	1440
15	Brick	20	Normal	MC-M	30	5	9.8	124.8	131.0	59.0	14.8	15.2	11.9	11.2	10.4	9.6	9.1	7.4	6.6	3.4	465
16	Brick	5	Normal	MC-M	5	5	10.3	124.1	136.0	68.0	14.8	15.9	12.7	12.0	11.3	11.0	10.5	10.1	9.7	9.5	1440
17	Brick	5	Normal	MC-M	20	5	10.0	124.6	130.0	63.0	14.8	15.8	12.5	12.5	11.3	11.5	10.9	10.7	9.6	8.6	1440
18	Brick	5	Normal	MC-M	30	5	9.9	124.7	125.0	60.0	14.8	14.7	12.3	12.1	11.7	11.5	10.7	11.0	10.7	9.8	1440
19	Brick	20	Wet	MC-M	5	5	10.3	124.3	134.0	68.0	14.7	14.3	13.2	12.4	11.8	11.3	11.3	10.7	9.6	7.9	1440
20	Brick	20	Wet	MC-M	20	5	9.4	125.4	135.0	66.0	14.8	14.8	13.0	12.0	11.1	10.8	10.8	10.4	10.8	9.2	1440
21	Brick	20	Wet	MC-M	30	5	9.4	125.3	131.0	61.0	14.8	14.0	12.8	11.7	10.9	10.9	10.5	10.6	10.8	10.3	1440
22	Brick	5	Wet	MC-M	5	5	10.8	123.5	137.0	69.0	14.8	14.4	12.4	11.6	11.3	11.3	11.0	10.1	10.0	10.0	1440
23	Brick	5	Wet	MC-M	20	5	9.2	125.7	128.0	62.0	14.8	14.6	13.1	12.6	12.1	11.6	11.8	11.1	10.9	10.1	1440
24	Brick	5	Wet	MC-M	30	5	10.1	124.4	133.0	65.0	14.8	14.9	13.2	12.2	11.1	11.2	10.7	10.7	10.3	8.4	1440
25	Brick	20	Dry	MC-M	20	20															
26	Brick	20	Normal	MC-M	20	20															
27	Brick	20	Wet	MC-M	20	20															
28	CMU A	20	Dry	MC-M	20	20	9.5	125.3	128.0	63.0	14.8	14.9	12.1	10.6	9.4	8.4	7.4	4.6	2.1	0.0	90
29	CMU B	20	Dry	MC-M	20	20	9.1	125.8	129.0	65.0	14.8	14.9	11.2	9.6	7.4	6.1	5.8	2.8	1.5	0.0	80
30	CMU C	20	Dry	MC-M	20	20	8.5	126.6	131.0	60.0	14.8	14.5	11.7	11.6	9.8	8.2	8.2	5.4	2.2	0.0	57

APPENDIX B: BOND STRENGTH OF MORTAR JOINTS

NCMA CPAR Project Sections 1.2.4 & 2.2. September 1995

Mortar bond strength according to ASTM

Moist %	*Resisting moment (kgf-m)*	*Comp. bond strength (MPa)*	*Tens. bond strength (MPa)*	*Comp. bond strength (psi)*	*Tens. bond strength (psi)*
16%, no freeze	12.49	2.39	0.23	346.7	34.0
16%, freeze	13.86	2.65	0.26	384.6	37.8
10%, freeze	11.08	2.12	0.21	307.6	30.1
8%, freeze	8.27	1.58	0.15	229.7	22.3
6%, freeze	10.79	2.07	0.20	299.6	29.3
KC1, no freeze	31.57	6.04	0.60	875.3	86.9
KC1, –5°C freeze	27.93	5.34	0.53	774.5	76.8
KC1, –10°C freeze	22.82	4.36	0.43	632.9	62.6

Note: The 16% no freeze and 16% freeze were retested because of excessive spread of test results.

Mortar bond strength according to ASTM Set Avg (ASTM)

Moist %	*Resisting moment (kgf-m)*	*Comp. bond strength (MPa)*	*Tens. bond strength (MPa)*	*Comp. bond strength (psi)*	*Tens. bond strength (psi)*
16%, no freeze	18.71	3.58	0.35	519.0	51.2
16%, no freeze	14.6	2.79	0.27	405.1	39.9
16%, no freeze	9.71	1.86	0.18	269.6	26.3
16%, no freeze	9.71	1.86	0.18	269.6	26.3
16%, no freeze	9.71	1.86	0.18	269.6	26.3
16%, freeze	18.71	3.58	0.35	519.0	51.2
16%, freeze	12.2	2.33	0.23	338.6	33.2
16%, freeze	12.2	2.33	0.23	338.6	33.2
16%, freeze	13.4	2.56	0.25	371.9	36.5
16%, freeze	12.8	2.45	0.24	355.2	34.9
10%, freeze	4.98	0.96	0.09	138.6	13.2
10%, freeze	13.88	2.66	0.26	385.2	37.9
10%, freeze	13.4	2.56	0.25	371.9	36.5
10%, freeze	14.48	2.77	0.27	401.8	39.5
10%, freeze	8.67	1.66	0.16	240.8	23.4
8%, freeze	6.18	1.18	0.11	171.8	16.5
8%, freeze	8.97	1.72	0.17	249.1	24.3
8%, freeze	10.74	2.06	0.20	298.2	29.2
8%, freeze	6.78	1.30	0.13	188.5	18.2
8%, freeze	8.67	1.66	0.16	240.8	23.4
6%, freeze	6.78	1.30	0.13	188.5	18.2
6%, freeze	6.78	1.30	0.13	188.5	18.2
6%, freeze	15.47	2.96	0.29	429.2	42.3
6%, freeze	16.67	3.19	0.31	462.5	45.6
6%, freeze	8.25	1.58	0.15	229.2	22.3
KC1, no freeze	33.03	6.31	0.63	915.8	90.9
KC1, no freeze	33.1	6.33	0.63	917.7	91.1
KC1, no freeze	34.7	6.63	0.66	962.0	95.5
KC1, no freeze	30.11	5.76	0.57	834.9	82.8
KC1, no freeze	26.92	5.15	0.51	746.5	74.0
KC1, –5°C freeze	26.92	5.15	0.51	746.5	74.0
KC1, –5°C freeze	29.34	5.61	0.56	813.5	80.7
KC1, –5°C freeze	26.92	5.15	0.51	746.5	74.0
KC1, –5°C freeze	31.85	6.09	0.60	883.1	87.6
KC1, –5°C freeze	24.6	4.70	0.47	682.2	67.6
KC1, –10°C freeze	23.45	4.48	0.44	650.3	64.4
KC1, –10°C freeze	20.18	3.86	0.38	559.7	55.3
KC1, –10°C freeze	20.18	3.86	0.38	559.7	55.3
KC1, –10°C freeze	28.25	5.40	0.54	783.3	77.7
KC1, –10°C freeze	22.03	4.21	0.42	611.0	60.4

APPENDIX C: ASTM C 1262, "STANDARD TEST METHOD FOR EVALUATING THE FREEZE–THAW DURABILITY OF MANUFACTURED CONCRETE MASONRY UNITS AND RELATED CONCRETE UNITS"

Standard Test Method for Evaluating the Freeze-Thaw Durability of Manufactured Concrete Masonry Units and Related Concrete Units[1]

This standard is issued under the fixed designation C 1262; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the freeze-thaw durability of manufactured concrete masonry and related concrete units. Units are tested either in water or in a saline solution depending on the intended use of the units in actual service.

NOTE 1—Concrete masonry and related concrete units include units such as hollow and solid concrete masonry units, concrete brick, segmental retaining wall units, concrete pavers, and concrete roof pavers.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Document

2.1 *ASTM Standard:*

C 140 Test Methods of Sampling and Testing Concrete Masonry Units[2]

3. Significance and Use

3.1 The procedure described in this test method is intended to determine the effects of concrete unit properties on the freeze-thaw durability of concrete units.

3.2 The procedure is not intended to provide a quantitative measure of the length of service that may be expected from a specific type of concrete unit.

4. Apparatus

4.1 *Freezing-and-Thawing Apparatus:*

4.1.1 In the event that a chamber or chambers are used to subject the specimens to the specified freezing or thawing cycles, or both, the chamber or chambers should be capable of maintaining the air temperature throughout the chamber within the specified test ranges when measured at any given time. If the apparatus operates automatically it must be able to provide reproducible cycles within the specified temperature requirements.

4.1.2 The apparatus includes a nonrigid plastic container for each test specimen and test specimen supports as illustrated in Fig. 1. The containers shall be of sufficient size to provide a minimum of ⅛ in. (3 mm) and a maximum of 1½ in. water surrounding the specimen. Test specimen supports to hold the specimen above the container bottom shall be two ⅛ in. (3 mm) rods of a noncorrosive, nonabsorptive material (brass, plastic, etc.). The container should be flat enough that when the specimen coupon is set on the support rods the specimen should not deviate from level by more than 1/16 in. (1.5 mm) from one end of the specimen to the opposite end.

4.2 *Temperature-Measuring Equipment*—Thermometers, resistance thermometers, or thermocouples, capable of measuring the temperature at various points within the test chamber to within 2°F (1.1°C).

4.3 *Scales*—Scales for weighing full-size specimens shall have a capacity of at least 50 % greater than the weight of the largest specimen tested and shall be accurate to at least 1 g (0.002 lb). Scales for weighing the filter paper and specimen residue (spall), as required in 7.2.8 and 7.2.11, shall be accurate to at least 0.2 g (0.0005 lb).

5. Sampling

5.1 *Selection of Test Specimens*—Select whole unit test specimens representative of the lot from which they are selected that are free from visible cracks or structural defects.

5.2 *Number of Specimens*—Select a sufficient number of units to obtain the necessary specimens to complete the freeze-thaw tests as well as the strength and absorption test of Test Methods C 140. Five units shall be used for freeze-thaw tests. Specimens (coupons) used for C 140 tests shall not be used for freeze-thaw specimens.

5.3 *Identification*—Mark each specimen so that it may be identified at any time.

6. Preparation of Test Specimens

6.1 *Compressive Strength and Absorption Test Specimens*—Preparation of specimens for compressive strength and absorption tests shall be in accordance with Test Methods C 140.

6.2 *Freeze-Thaw Test Specimens*—Test specimens shall consist of solid coupons saw cut from full-sized units. Do not saw-cut test specimens from units that have been previously oven-dried. Do not subject test specimens to oven-drying prior to completion of freeze-thaw testing.

6.2.1 One coupon shall be cut from each of the five sampled units. Using a water-cooled saw, cut the coupon from the exposed surface of the unit as the unit is used in service unless the exposed surface is a split, fluted (ribbed), or other nonplanar surface. In the case of a unit with an exposed nonplanar surface, cut the coupon from another flat molded surface. This exposed surface (or other flat molded surface in the case of a unit with an exposed face) will

[1] This test method is under the jurisdiction of ASTM Committee C-15 on Manufactured Masonry Units and is the direct responsibility of Subcommittee C15.03 on Concrete Masonry Units and Related Units.

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[2] *Annual Book of ASTM Standards*. Vol 04.05.

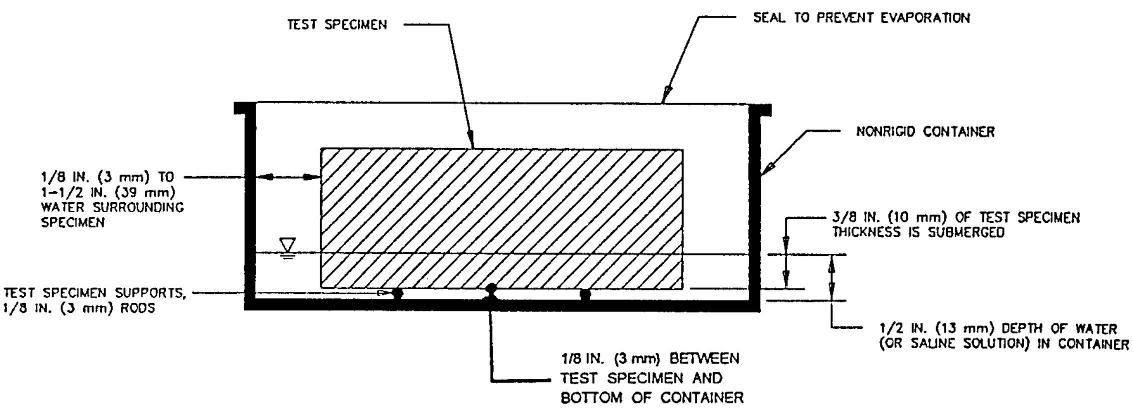

FIG. 1 Test Specimen in Freeze-thaw Container

become the submerged surface of the test specimen.

6.2.2 The thickness of each coupon shall be 1¼ in. (32 mm) ± 1/16 in. (2 mm), unless the unit does not permit this minimum thickness, in which case the thickness shall be the maximum thickness that can be obtained from the unit.

6.2.3 The area of the submerged surface of the test specimen shall be at least 25 in.^{2} (161 cm^2) and shall not exceed 35 in.^{2} (225 cm^2), unless the unit does not permit a coupon meeting the minimum area, in which case the test specimen shall consist of two coupons. The combined area of the two coupons shall be at least 25 in.^{2} (161 cm^2) and shall not exceed 35 in.^{2} (225 cm^2). These two coupons shall be tested as and considered to be a single specimen.

7. Procedure

7.1 *Compressive Strength and Absorption Tests*—Compressive strength and absorption tests shall be in accordance with Test Methods C 140.

7.2 *Freeze-Thaw Tests:*

7.2.1 After preparation of the freeze-thaw test specimens in accordance with 6.2, completely submerge each specimen in water at a temperature of 60 to 80°F (16 to 27°C) for 48 h.

7.2.2 Remove the specimen from the water and allow to drain for 1 min by placing it on a ⅜-in. (9.5 mm) or coarser mesh, removing visible surface water with a damp cloth. Immediately weigh the specimen to the nearest 1 g (0.002 lb) and record as W_s.

7.2.3 Place the saturated specimens in the container(s) face down on the specimen supports such that the non-saw-cut surface of the specimen is in contact with the specimen supports. Adjust the level of water in the container to be ½ in. (13 mm) deep. During the testing the specimen container should be on a level surface so that the submerged portion of the specimen is ⅜ ± 1/16 in. (9.5 ± 1.5 mm) on all sides of the specimen. For test specimens being evaluated for freeze-thaw resistance in saline solutions use a 3 % saline solution in lieu of water in the container. Seal the container to prevent evaporation.

NOTE 2—The submerged portion of the specimen is ⅜ in. (9.5 mm) of its thickness. There is ⅛ in. (3.2 mm) of water between the bottom of the container and the face of the specimen.

7.2.4 Prior to beginning the test, the test specimens and the water surrounding the specimens shall be at 70 ± 5°F (21.1 ± 2.8°C).

7.2.5 Begin the test with a freeze cycle. Place the specimens (within the specimen containers) into the freezing test chamber such that each specimen container is surrounded by a minimum air space of ½ in. (12.7 mm) on all sides. During the freeze cycle, maintain the air temperature in the chamber at 5 ± 5°F (−15 ± 2.8°C) for a period of not less than 4.0 h and not more than 5.0 h.

7.2.6 After the freeze cycle, immediately begin the thaw cycle. During the thaw cycle, maintain the air temperature around the specimen containers at 65 to 75°F (18.3 to 23.9°C) for a period of not less than 2.5 h and not more than 72 h. Each specimen container shall be surrounded by a minimum air space of ½ in. on all sides. If the air surrounding the specimen containers is not continuously circulated during the thaw cycle, the containers shall be laid out in a single layer without stacking in the vertical direction.

7.2.7 One freeze-thaw cycle is defined as a completed freeze cycle followed by a completed thaw cycle. Repeat the freeze-thaw cycle a total of 8 to 12 times.

7.2.8 After the 8 to 12 freeze-thaw cycles, remove a single specimen from its container. Immediately rinse the specimen with water (if the specimen is tested in saline solution, use saline solution to rinse the specimen) being careful to collect in the specimen container the rinse water and all loose particles from the specimen. Weigh to the nearest 0.2 g (0.0005 lb) and record as W_f a filter paper of high wet strength and smooth surface that has come to equilibrium temperature with the lab environment. Pour the water (or saline solution) from the specimen container through the filter paper to collect the residue (spall) from the test specimen. Continue to rinse the specimen container and pour the rinse water through the filter paper until all residue (spall) in the specimen container is collected on the filter paper. Rinse the residue from specimens tested in saline solution three times with distilled water to remove any soluble salt. During this rinsing and filtering procedure, make sure the specimen is maintained in a wet condition by placing it in an empty specimen container and keeping it covered to prevent evaporation.

NOTE 3—The filtering may be expedited by using filter paper rated at a faster speed, or a vacuum filtration set-up, or both. This is acceptable as long as the water that passes through the filter paper (filtrate) is clear

to the naked eye. If it is cloudy, then filter papers of increasingly slower speeds should be used until the filtrate is clear.

7.2.9 Return the specimen to the container positioned on its supports. Check that the specimen container still meets the flatness requirement of 4.1.2. If it fails to meet the flatness requirement, use a different container. Add fresh water (or saline solution) to the container in accordance with 7.2.3 and seal the container.

7.2.10 Repeat the procedures described in 7.2.8 and 7.2.9 with each remaining specimen.

7.2.11 Dry all the filter paper and residue (spall) collected from each specimen at 212 to 239°F (100 to 115°C) for 2 to 4 h. Place the filter paper and residue in a draft-free location within the laboratory for a period of two hours to allow the filter paper and residue to come to equilibrium temperature with the laboratory environment. Weigh to the nearest 0.2 g (0.0005 lb) and record as W_{f+r} the filter paper and residue. Calculate the residue weight, W_r, as follows:

$$W_r = W_{f+r} - W_f \quad (1)$$

where:

W_r = weight of residue (spall), g (lb),
W_{f+r} = weight of the dried residue and filter paper, g (lb), and
W_f = initial weight of the filter paper, g (lb).

7.2.12 Repeat the procedures of 7.2.5 through 7.2.11 until the accumulated residue (spall) of a specimen exceeds 10 % (or other specified amount) of the initial saturated weight of the test specimen, or until the specified number of freeze-thaw cycles is complete.

7.2.13 At the completion of the freeze-thaw testing, dry each specimen at 212 to 239°F (100 to 115°C) for 24 ± 1 h. Weigh to the nearest 1 g (0.002 lb) the final oven-dried specimen and record as W_{final}. Calculate the initial weight of the specimen, $W_{initial}$, as follows:

$$W_{initial} = W_{final} + W_{residue} \quad (2)$$

where:

$W_{initial}$ = calculated initial weight of the specimen, g (lb),
W_{final} = final weight of the specimen, g (lb), and
$W_{residue}$ = total accumulated residue weight (equal to the sum of the residue weight, W_r, from each evaluation period of 8 to 12 freeze-thaw cycles), g (lb).

8. Calculation and Report

8.1 Report compressive strength and absorption in accordance with Test Methods C 140.

8.2 Determine and report the weight loss for each 8 to 12 cycle interval and the cumulative weight loss after each 8 to 12 cycle interval expressed in terms of grams (pounds) and as a percent of the calculated initial weight of the specimen, $W_{initial}$, determined in accordance with 7.2.13. Where the coupon thickness is less than 1.25 in. (32 mm), the percentage and cumulative weight loss shall be multiplied by a value equal to the actual thickness in inches (mm) divided by 1.25 in. (32 mm). Report these values for each specimen as well as the average of the specimens tested.

8.3 Report whether test specimen is evaluated in water or in saline solution.

9. Precision

9.1 Precision data for freeze-thaw durability is not available.

10. Keywords

10.1 absorption; compressive strength; freeze-thaw durability; manufactured concrete units

APPENDIX D: MASONRY UNIT FREEZE–THAW DURABILITY TEST RESULTS

NCMA Research Lab: ASTM C 1262 Freeze–Thaw Data Sheet

Specimens: SRW (A)

		Cycle 145		*Cycle 283*		*Cycle 373*		*Cycle 448*		*Cycle 542*		*Cycle 818*		*Cycle 875*	
Unit no.	*SSD† wt. (lb)*	*Acc.* res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*
SRW (A)-1	2.9514	0.0040	0.1	0.0066	0.2	0.0106	0.4	0.0124	0.4	0.0148	0.5	0.0222	0.8	0.0236	0.8
SRW (A)-2	3.0012	0.0032	0.1	0.0048	0.2	0.0060	0.2	0.0072	0.2	0.0084	0.3	0.0136	0.5	0.0222	0.7
SRW (A)-3	3.0584	0.0032	0.1	0.0048	0.2	0.0058	0.2	0.0068	0.2	0.0074	0.2	0.0104	0.3	0.0118	0.4
SRW (A)-4	3.0882	0.0032	0.1	0.0048	0.2	0.0058	0.2	0.0070	0.2	0.0080	0.3	0.0118	0.4	0.0138	0.4
SRW (A)-5	3.0884	0.0018	0.1	0.0028	0.1	0.0032	0.1	0.0036	0.1	0.0042	0.1	0.0062	0.2	0.0066	0.2
SRW (A)-6	3.1062	0.0012	0.0	0.0022	0.1	0.0024	0.1	0.0030	0.1	0.0034	0.1	0.0052	0.2	0.0058	0.2
SRW (A)-7	3.1480	0.0028	0.1	0.0042	0.1	0.0050	0.2	0.0056	0.2	0.0062	0.2	0.0094	0.3	0.0098	0.3
SRW (A)-8	3.1530	0.0040	0.1	0.0070	0.2	0.0080	0.3	0.0094	0.3	0.0102	0.3	0.0144	0.5	0.0162	0.5
SRW (A)-9	3.0760	0.0044	0.1	0.0062	0.2	0.0070	0.2	0.0080	0.3	0.0082	0.3	0.0120	0.4	0.0130	0.4
SRW (A)-10	3.2016	0.0044	0.1	0.0064	0.2	0.0078	0.2	0.0086	0.3	0.0094	0.3	0.0132	0.4	0.0142	0.4
Avg.	3.0872		0.1		0.2		0.2		0.2		0.3				
SD	0.0695														
COV	2.2504														

* Accumulated residual weight.
† Saturated, surface dry.

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Specimens: SRW (G)

		Cycle 76		*Cycle 102*		*Cycle 172*		*Cycle 216*		*Cycle 246*		*Cycle 266*	
Unit no.	*SSD wt. (lb)*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*
SRW (G2)-1	3.1252	0.0318	1.0	0.0448	1.4	0.0664	2.1	0.0808	2.6	0.0894	2.9		
SRW (G2)-2	3.0604	0.0246	0.8	0.0348	1.1	0.0584	1.9	0.0914	3.0	0.1860	6.1	0.2632	8.6
SRW (G2)-3	3.2350	0.0156	0.5	0.0186	0.6	0.0272	0.8	0.0348	1.1	0.0384	1.2		
SRW (G2)-4	3.1022	0.0352	1.1	0.0496	1.6	0.0650	2.1	0.0730	2.4	0.0788	2.5		
SRW (G2)-5	3.2304	0.0240	0.7	0.0306	0.9	0.0396	1.2	0.0460	1.4	0.0494	1.5		
SRW (G2)-6	3.2456	0.0362	1.1	0.0454	1.4	0.0582	1.8	0.0704	2.2	0.0786	2.4		
SRW (G2)-7	3.2744	0.0314	1.0	0.0392	1.2	0.0528	1.6	0.0618	1.9	0.0652	2.0		
SRW (G2)-8	3.1954	0.0248	0.8	0.0336	1.1	0.0508	1.6	0.0580	1.8	0.0646	2.0		
SRW (G2)-9	3.2566	0.0160	0.5	0.0200	0.6	0.0314	1.0	0.0396	1.2	0.0468	1.4		
SRW (G2)-10	3.2800	0.0354	1.1	0.0450	1.4	0.0584	1.8	0.0698	2.1	0.0818	2.5		
Avg.	3.2005												
SD	0.0735												
COV	2.2967												

	Cycle 274		*Cycle 286*		*Cycle 307*		*Cycle 333*		*Cycle 362*		*Cycle 397*		*Cycle 436*	
Unit no.	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*
SRW (G2)-1			0.0964	3.1	0.1026	3.3	0.1102	3.5	0.1180	3.8	0.1338	4.3	0.1532	4.9
SRW (G2)-2	0.3288	10.7												
SRW (G2)-3			0.0484	1.5	0.0510	1.6	0.0580	1.8	0.0614	1.9	0.0684	2.1	0.0812	2.5
SRW (G2)-4			0.0846	2.7	0.0898	2.9	0.0964	3.1	0.1048	3.4	0.1234	4.0	0.1440	4.6
SRW (G2)-5			0.0560	1.7	0.0596	1.8	0.0676	2.1	0.0712	2.2	0.0786	2.4	0.0944	2.9
SRW (G2)-6			0.0902	2.8	0.0954	2.9	0.1056	3.3	0.1144	3.5	0.1288	4.0	0.1482	4.6
SRW (G2)-7			0.0738	2.3	0.0756	2.3	0.0794	2.4	0.0848	2.6	0.0910	2.8	0.1074	3.3
SRW (G2)-8			0.0728	2.3	0.0792	2.5	0.0846	2.6	0.0950	3.0	0.1096	3.4	0.1284	4.0
SRW (G2)-9			0.0534	1.6	0.0560	1.7	0.0606	1.9	0.0642	2.0	0.0718	2.2	0.0850	2.6
SRW (G2)-10			0.1014	3.1	0.1116	3.4	0.1240	3.8	0.1324	4.0	0.1422	4.3	0.1584	4.8

	Cycle 490		*Cycle 525*		*Cycle 590*		*Cycle 669*		*Cycle 798*		*Cycle 907*	
Unit no.	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*
SRW (G2)-1	0.1696	5.4	0.1852	5.9	0.2090	6.7	0.2386	7.6	0.2770	8.9	0.3206	10.3
SRW (G2)-2												
SRW (G2)-3	0.0954	2.9	0.1082	3.3	0.1248	3.9	0.1650	5.1	0.2208	6.8	0.2718	8.4
SRW (G2)-4	0.1674	5.4	0.1818	5.9	0.2028	6.5	0.2322	7.5	0.2682	8.6	0.2990	9.6
SRW (G2)-5	0.1046	3.2	0.1102	3.4	0.1300	4.0	0.1476	4.6	0.1690	5.2	0.1764	5.5
SRW (G2)-6	0.1652	5.1	0.1792	5.5	0.2002	6.2	0.2300	7.1	0.2668	8.2	0.2946	9.1
SRW (G2)-7	0.1260	3.8	0.1412	4.3	0.1564	4.8	0.1888	5.8	0.2274	6.9	0.2472	7.5
SRW (G2)-8	0.1480	4.6	0.1654	5.2	0.1838	5.8	0.2044	6.4	0.2498	7.8	0.2794	8.7
SRW (G2)-9	0.0920	2.8	0.0966	3.0	0.1096	3.4	0.1246	3.8	0.1548	4.8	0.1874	5.8
SRW (G2)-10	0.1732	5.3	0.1932	5.9	0.2080	6.3	0.2496	7.6	0.2820	8.6	0.3158	9.6

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Specimens: SRW (H)

Unit no.	SSD wt. (lb)	Cycle 73 Acc. res. wt. (lb)	Cycle 73 % loss from SSD	Cycle 140 Acc. res. wt. (lb)	Cycle 140 % loss from SSD	Cycle 184 Acc. res. wt. (lb)	Cycle 184 % loss from SSD	Cycle 244 Acc. res. wt. (lb)	Cycle 244 % loss from SSD	Cycle 305 Acc. res. wt. (lb)	Cycle 305 % loss from SSD	Cycle 360 Acc. res. wt. (lb)	Cycle 360 % loss from SSD
SRW (H)-1	3.0894	0.0150	0.5	0.0350	1.1	0.0440	1.4	0.0566	1.8	0.0666	2.2	0.0768	2.5
SRW (H)-2	3.2062	0.0072	0.2	0.0136	0.4	0.0172	0.5	0.0230	0.7	0.0284	0.9	0.0342	1.1
SRW (H)-3	3.1532	0.0058	0.2	0.0154	0.5	0.0208	0.7	0.0268	0.8	0.0358	1.1	0.0430	1.4
SRW (H)-4	3.1920	0.0114	0.4	0.0216	0.7	0.0260	0.8	0.0320	1.0	0.0384		0.0440	1.4
SRW (H)-5	2.9938	0.0148	0.5	0.0280	0.9	0.0348	1.2	0.0412	1.4	0.0536	1.8	0.0654	2.2
SRW (H)-6	3.0822	0.0224	0.7	0.0332	1.1	0.0426	1.4	0.0514	1.7	0.0586	1.9	0.0728	2.4
SRW (H)-7	3.0982	0.0080	0.3	0.0132	0.4	0.0188	0.6	0.0242	0.8	0.0306	1.0	0.0380	1.2
SRW (H)-8	3.1036	0.0068	0.2	0.0154	0.5	0.0210	0.7	0.0254	0.8	0.0322	1.0	0.0410	1.3
SRW (H)-9	3.0942	0.0176	0.6	0.0316	1.0	0.0418	1.4	0.0524	1.7	0.0656	2.1	0.0786	2.5
SRW (H)-10	3.0892	0.0234	0.8	0.0426	1.4	0.0540	1.7	0.0676	2.2	0.0834	2.7	0.0972	3.1
Avg.	3.1102												
SD	0.0578												
COV	1.8583												

Unit no.	Cycle 395 Acc. res. wt. (lb)	Cycle 395 % loss from SSD	Cycle 434 Acc. res. wt. (lb)	Cycle 434 % loss from SSD	Cycle 481 Acc. res. wt. (lb)	Cycle 481 % loss from SSD	Cycle 605 Acc. res. wt. (lb)	Cycle 605 % loss from SSD	Cycle 729 Acc. res. wt. (lb)	Cycle 729 % loss from SSD	Cycle 920 Acc. res. wt. (lb)	Cycle 920 % loss from SSD	Cycle 938 Acc. res. wt. (lb)	Cycle 938 % loss from SSD
SRW (H)-1	0.0814	2.6	0.0896	2.9	0.0976	3.2	0.1116	3.6	0.1352	4.4	0.1570	5.1	0.1594	5.2
SRW (H)-2	0.0366	1.1	0.0412	1.3	0.0448	1.4	0.0536	1.7	0.0600	1.9	0.0770	2.4	0.0780	2.4
SRW (H)-3	0.0458	1.5	0.0514	1.6	0.0554	1.8	0.0700	2.2	0.0792	2.5	0.0968	3.1	0.0982	3.1
SRW (H)-4	0.0484	1.5	0.0548	1.7	0.0590	1.8	0.0742	2.3	0.0894	2.8	0.1080	3.4	0.1088	3.4
SRW (H)-5	0.0720	2.4	0.0866	2.9	0.0932	3.1	0.1144	3.8	0.1290	4.3	0.1548	5.2	0.1564	5.2
SRW (H)-6	0.0774	2.5	0.0914	3.0	0.0994	3.2	0.1178	3.8	0.1618	5.2	0.1944	6.3	0.1996	6.5
SRW (H)-7	0.0426	1.4	0.0498	1.6	0.0538	1.7	0.0710	2.3	0.0842	2.7	0.0968	3.1	0.0978	3.2
SRW (H)-8	0.0460	1.5	0.0530	1.7	0.0596	1.9	0.0698	2.2	0.0822	2.6	0.0958	3.1	0.0968	3.1
SRW (H)-9	0.0854	2.8	0.0946	3.1	0.1028	3.3	0.1194	3.9	0.1364	4.4	0.1674	5.4	0.1704	5.5
SRW (H)-10	0.1042	3.4	0.1146	3.7	0.1200	3.9	0.1344	4.4	0.1482	4.8	0.1656	5.4	0.1678	5.4

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Specimens: SRW (I)

		Cycle 41		Cycle 56		Cycle 64		Cycle 73		Cycle 81	
Unit no.	SSD wt. (lb)	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD
SRW (I)-1	2.7876	0.0188	0.7	0.0676	2.4	0.1680	6.0	0.3872	13.9	—	
SRW (I)-2	2.8026	0.0106	0.4	0.0396	1.4	0.0850	3.0	0.1686	6.0	0.3852	13.7
SRW (I)-3	2.8506	0.0058	0.2	0.0096	0.3	0.0148	0.5	0.0287	1.0	0.0470	1.6
SRW (I)-4	2.8772	0.0140	0.5	0.0490	1.7	0.0682	2.4	0.2234	7.8	0.4028	14.0
SRW (I)-5	2.8054	0.0058	0.2	0.0084	0.3	0.0160	0.6	0.0314	1.1	0.2270	8.1
SRW (I)-6	2.8338	0.0084	0.3	0.0126	0.4	0.0164	0.6	0.0254	0.9	0.0414	1.5
SRW (I)-7	2.7914	0.0064	0.2	0.0134	0.5	0.0240	0.9	0.0394	1.4	0.0736	2.6
SRW (I)-8	2.7344	0.0066	0.2	0.0190	0.7	0.0536	2.0	0.2324	8.5	0.3820	14.0
SRW (I)-9	2.8206	0.0086	0.3	0.0268	1.0	0.0374	1.3	0.1618	5.7	0.2886	10.2
SRW (I)-10	2.7540	0.0156	0.6	0.0644	2.3	0.2246	8.2	0.3840	13.9	—	
Avg.	2.8058										
SD	0.0405										
COV	1.4450										

	Cycle 89		Cycle 94		Cycle 100		Totals	
Unit no.	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Failure cycle (lb)	% loss from SSD
SRW (I)-1	—		—		—		73	13.9
SRW (I)-2	—		—		—		81	13.7
SRW (I)-3	0.0610	2.1	0.2430	8.5	0.3092	10.8	100	10.8
SRW (I)-4	—		—		—		81	14.0
SRW (I)-5	0.3010	10.7	—		—		89	10.7
SRW (I)-6	0.0654	2.3	0.1414	5.0	0.2946	10.4	100	10.4
SRW (I)-7	0.2282	8.2	0.2944	10.5	—		94	10.5
SRW (I)-8	—		—		—		81	14.0
SRW (I)-9	—		—		—		81	10.2
SRW (I)-10	—		—		—		73	13.9

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Specimens: SRW (J)

		Cycle 52		*Cycle 57*		*Cycle 61*		*Cycle 67*		*Cycle 69*	
Unit no.	*SSD wt. (lb)*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*	*Acc. res. wt. (lb)*	*% loss from SSD*
SRW (J)-1	2.7968	0.0148	0.5	0.0210	0.8	0.0284	1.0	0.1292	4.6	0.1722	6.2
SRW (J)-2	2.7424	0.0234	0.9	0.0320	1.2	0.0492	1.8	0.2436	8.9	0.4044	14.7
SRW (J)-3	2.8282	0.0214	0.8	0.0328	1.2	0.0464	1.6	0.0932	3.3	0.1660	5.9
SRW (J)-4	2.7922	0.0168	0.6	0.0286	1.0	0.0394	1.4	0.1066	3.8	0.1424	5.1
SRW (J)-5	2.7830	0.0188	0.7	0.0340	1.2	0.0434	1.6	0.1366	4.9	0.2814	10.1
SRW (J)-6	2.9644	0.0612	2.1	0.1052	3.5	0.1318	4.4	0.2750	9.3	0.3272	11.0
SRW (J)-7	2.8082	0.0632	2.3	0.1328	4.7	0.1906	6.8	0.7478	26.6	—	
SRW (J)-8	2.7942	0.0080	0.3	0.0130	0.5	0.0202	0.7	0.1342	4.8	0.2312	8.3
SRW (J)-9	2.8408	0.0122	0.4	0.0302	1.1	0.0498	1.8	0.1912	6.7	0.3018	10.6
SRW (J)-10	2.9749	0.0986	3.3	0.1294	4.3	0.1484	5.0	0.3662	12.3	—	
Avg.	2.8325										
SD	0.0730										
COV	2.5771										

	Cycle 72		*Totals*	
Unit no.	*Acc. res. wt. (lb)*	*% loss from SSD*	*Failure cycle (lb)*	*% loss from SSD*
SRW (J)-1	0.2832	10.1	72	10.1
SRW (J)-2	—		69	14.7
SRW (J)-3	0.2994	10.6	72	10.6
SRW (J)-4	0.2832	10.1	72	10.1
SRW (J)-5	—		69	10.1
SRW (J)-6	—		69	11.0
SRW (J)-7	—		67	26.6
SRW (J)-8	0.3120	11.2	72	11.2
SRW (J)-9	—		69	10.6
SRW (J)-10	—		67	12.3

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Specimens: SRW (K)

Unit no.	SSD wt. (lb)	Cycle 47		Cycle 55		Cycle 63		Cycle 72		Cycle 80		Cycle 88	
		Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD
SRW (K)-1	2.6226	0.0064	0.2	nsl		0.0152	0.6	nsl		0.1330	5.1	0.3090	11.8
SRW (K)-2	2.6386	0.0060	0.2	nsl		0.0080	0.3	nsl		0.0152	0.6	0.2174	8.2
SRW (K)-3	2.5718	0.0626	2.4	0.4228	16.4	—		—		—		—	
SRW (K)-4	2.6870	0.0104	0.4	nsl		0.0354	1.3	0.1282	4.8	0.3352	12.5	—	
SRW (K)-5	2.5896	0.0054	0.2	nsl		0.0074	0.3	nsl		0.0144	0.6	0.0140	0.5
SRW (K)-6	2.5741	0.3870	15.0	—		—		—		—		—	
SRW (K)-7	2.6140	0.0150	0.6	nsl		0.0296	1.1	0.0414	1.6	0.0492	1.9	0.0768	2.9
SRW (K)-8	2.6050	0.0088	0.3	nsl		0.0190	0.7	0.0320	1.2	0.0706	2.7	0.1390	5.3
SRW (K)-9	2.6880	0.0066	0.2	nsl		0.0090	0.3	nsl		0.0146	0.5	0.0172	0.6
SRW (K)-10	2.6486	0.0082	0.3	nsl		0.0270	1.0	0.0606	2.3	0.2828	10.7	—	
Avg.	2.6239												
SD	0.0397												
COV	1.5122												

Unit no.	Cycle 93		Cycle 99		Cycle 108		Cycle 118		Cycle 127		Cycle 133	
	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD
SRW (K)-1	—		—		—		—		—		—	
SRW (K)-2	0.2964	11.2	—		—		—		—		—	
SRW (K)-3	—		—		—		—		—		—	
SRW (K)-4	—		—		—		—		—		—	
SRW (K)-5	nsl		0.0236	0.9	0.0676	2.6	0.1028	4.0	0.2228	8.6	0.3142	12.1
SRW (K)-6	—		—		—		—		—		—	
SRW (K)-7	0.0890	3.4	0.1252	4.8	0.3008	11.5	—		—		—	
SRW (K)-8	0.1848	7.1	0.2278	8.7	0.2700	10.4	—		—		—	
SRW (K)-9	nsl		0.0186	0.7	0.0246	0.9	0.0306	1.1	0.0398	1.5	0.0528	2.0
SRW (K)-10	—		—		—		—		—		—	

Unit no.	Cycle 138		Cycle 147		Cycle 156		Cycle 167		Cycle 179		Totals	
	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Acc. res. wt. (lb)	% loss from SSD	Failure cycle (lb)	% loss from SSD
SRW (K)-1	—										88	11.8
SRW (K)-2	—										93	11.2
SRW (K)-3	—										55	16.4
SRW (K)-4	—										80	12.5
SRW (K)-5	—										133	12.1
SRW (K)-6	—										47	15.0
SRW (K)-7	—										108	11.5
SRW (K)-8	—										108	10.4
SRW (K)-9	0.0598	2.2	0.0720	2.7	0.1038	3.9	0.1530	5.7	0.3232	12.0	179	12.0
SRW (K)-10	—										80	10.7

APPENDIX E: AIR-VOID ANALYSES
ASTM C 457, Modified Point Count Method

NCMA-SRW-A10

Traverse no.	Cum. no. of points landing on: Fine aggregate	Cement paste	Total air	Cumulative total no. of points	Volume fractions (%): Fine aggregate	Cement paste	Total air	No. of inter-connected air voids
1	27	26	6	59	45.8	44.1	10.2	27
2	53	42	22	117	45.3	35.9	18.8	49
3	85	57	35	177	48.0	32.2	19.8	71
4	113	77	46	236	47.9	32.6	19.5	91
5	147	94	54	295	49.8	31.9	18.3	114
6	177	117	61	355	49.9	33.0	17.2	132
7	212	134	69	415	51.1	32.3	16.6	146
8	245	151	77	473	51.8	31.9	16.3	162
9	279	167	88	534	52.2	31.3	16.5	178
10	314	185	98	597	52.6	31.0	16.4	202

Total length of traverse (T) = (Total no. of points – No. of traverse lines) * Grid interval = 372.2 mm
Voids/mm = $n = N/T$ = 0.54
Specific surface in $mm^2/mm^3 = 4/l$ = 13.21
Average chord intercept (l) in mm = $A/100\ n$ = 0.30
Paste/air ratio (p/A) = 1.888 <4.342
If p/A >4.342, then spacing factor (L) = 226 µm
If p/A <4.342, then spacing factor (L) = 143 µm

Conclusion: Air content is high. Spacing factor is small (good). Most of the aggregate is quartzite, well graded, and apparently sound. The air void system in the cement paste is good and aggregate is of good quality. Good F-T resistance is expected.

NCMA-SRW-G1

Traverse no.	Cum. no. of points landing on: Fine aggregate	Cement paste	Total air	Cumulative total no. of points	Volume fractions (%): Fine aggregate	Cement paste	Total air	No. of inter-connected air voids
1	36	7	1	44	81.8	15.9	2.3	6
2	60	18	9	87	69.0	20.7	10.3	18
3	90	25	13	128	70.3	19.5	10.2	31
4	118	36	18	172	68.6	20.9	10.5	42
5	151	46	19	216	69.9	21.3	8.8	51
6	178	56	23	257	69.3	21.8	8.9	64
7	207	64	29	300	69.0	21.3	9.7	75
8	238	71	32	341	69.8	20.8	9.4	85
9	264	80	38	382	69.1	20.9	9.9	97
10	288	96	41	425	67.8	22.6	9.6	109

Total length of traverse (T) = (Total no. of points – No. of traverse lines) * Grid interval = 263.5 mm
Voids/mm = $n = N/T$ = 0.41
Specific surface in $mm^2/mm^3 = 4/l$ = 17.15
Average chord intercept (l) in mm = $A/100\ n$ = 0.23
Paste/air ratio (p/A) = 2.341 <4.342
If p/A >4.342, then spacing factor (L) = 191 µm
If p/A <4.342, then spacing factor (L) = 137 µm

Conclusion: Air content is low. Spacing factor is low (good). Based on air voids in the paste alone, adequate F-T resistance is expected. The aggregate appears to be sound, well graded, well packed, and angular. Paste/air ratio is low.

NCMA-SRW-H1

Traverse no.	*Cum. no. of points landing on* Fine aggregate	Cement paste	Total air	*Cumulative* total no. of points	*Volume fractions (%)* Fine aggregate	Cement paste	Total air	*No. of inter-connected air voids*
1	28	14	1	43	65.1	32.6	2.3	6
2	57	27	3	87	65.5	31.0	3.4	14
3	85	39	4	128	66.4	30.5	3.1	21
4	111	52	6	169	65.7	30.8	3.6	27
5	141	60	9	210	67.1	28.6	4.3	36
6	174	67	13	254	68.5	26.4	5.1	48
7	198	82	15	295	67.1	27.8	5.1	56
8	229	92	15	336	68.2	27.4	4.5	60
9	255	105	17	377	67.6	27.9	4.5	66
10	282	118	19	419	67.3	28.2	4.5	71

Total length of traverse (T) = (Total no. of points – No. of traverse lines) * Grid interval = 259.7 mm
Voids/mm = $n = N/T = 0.27$
Specific surface in mm^2/mm^3 = $4/l = 24.11$
Average chord intercept (l) in mm = $A/100\ n = 0.17$
Paste/air ratio (p/A) = 6.211 >4.342
If p/A >4.342, then spacing factor (L) = 212 µm
If p/A <4.342, then spacing factor (L) = 258 µm

Conclusion: Air content is low. Spacing factor is low (good). Based on air voids in the paste alone, adequate F-T resistance is expected. The aggregate appears to be sound, well graded, well packed, and angular. Paste/air ratio is low.

NCMA-SRW-I10

Traverse no.	*Cum. no. of points landing on* Fine aggregate	Cement paste	Total air	*Cumulative* total no. of points	*Volume fractions (%)* Fine aggregate	Cement paste	Total air	*No. of inter-connected air voids*
1	29	8	4	41	70.7	19.5	9.8	11
2	54	19	9	82	65.9	23.2	11.0	30
3	70	37	17	124	56.5	29.8	13.7	47
4	93	49	23	165	56.4	29.7	13.9	67
5	116	63	27	206	56.3	30.6	13.1	77
6	138	78	31	247	55.9	31.6	12.6	88
7	155	87	45	287	54.0	30.3	15.7	110
8	175	106	47	328	53.4	32.3	14.3	126
9	196	121	52	369	53.1	32.8	14.1	140
10	224	132	54	410	54.6	32.2	13.2	154

Total length of traverse (T) = (Total no. of points – No. of traverse lines) * Grid interval = 254 mm
Voids/mm = $n = N/T = 0.61$
Specific surface in mm^2/mm^3 = $4/l = 18.41$
Average chord intercept (l) in mm = $A/100\ n = 0.22$
Paste/air ratio (p/A) = 2.444 <4.342
If p/A >4.342, then spacing factor (L) = 182 µm
If p/A <4.342, then spacing factor (L) = 133 µm

Conclusion: Air content is low. Spacing factor is low (good). Based on air voids in the paste alone, adequate F-T resistance is expected. However, abundance of very porous (large-pored) aggregates may indicate questionable performance. Paste/air ratio is very low.

NCMA-SRW-J10

Traverse no.	*Cum. no. of points landing on* *Fine aggregate*	*Cement paste*	*Total air*	*Cumulative total no. of points*	*Volume fractions (%)* *Fine aggregate*	*Cement paste*	*Total air*	*No. of inter-connected air voids*
1	51	27	5	83	61.4	32.5	6.0	12
2	106	52	8	166	63.9	31.3	4.8	24
3	152	80	15	247	61.5	32.4	6.1	40
4	206	104	18	328	62.8	31.7	5.5	49
5	257	132	24	413	62.2	32.0	5.8	65
6	303	158	33	494	61.3	32.0	6.7	84
7	354	181	40	575	61.6	31.5	7.0	99
8	405	204	48	657	61.6	31.1	7.3	117
9	447	234	57	738	60.6	31.7	7.7	138
10	493	264	62	819	60.2	32.2	7.6	153

Total length of traverse (T) = (Total no. of points – No. of traverse lines) * Grid interval = 513.7 mm
Voids/mm = $n = N/T$ = 0.30
Specific surface in $mm^2/mm^3 = 4/l$ = 15.74
Average chord intercept (l) in mm = $A/100\ n$ = 0.25
Paste/air ratio (p/A) = 4.258 <4.342
If p/A >4.342, then spacing factor (L) = 273 µm
If p/A <4.342, then spacing factor (L) = 271 µm

Conclusion: Air content is very low. Spacing factor is larger than wanted. About 80% of the aggregate is white, relatively porous, and soft (Moh's hardness is 4). Questionable F-T resistance is expected.

NCMA-SRW-K

Traverse no.	*Cum. no. of points landing on* *Fine aggregate*	*Cement paste*	*Total air*	*Cumulative total no. of points*	*Volume fractions (%)* *Fine aggregate*	*Cement paste*	*Total air*	*No. of inter-connected air voids*
1	21	14	7	42	50.0	33.3	16.7	16
2	46	28	11	85	54.1	32.9	12.9	35
3	73	36	17	126	57.9	28.6	13.5	51
4	97	51	19	167	58.1	30.5	11.4	74
5	118	67	24	209	56.5	32.1	11.5	95
6	136	85	31	252	54.0	33.7	12.3	122
7	156	98	39	293	53.2	33.4	13.3	141
8	174	118	41	333	52.3	35.4	12.3	166
9	197	130	48	375	52.5	34.7	12.8	192
10	217	147	54	418	51.9	35.2	12.9	215

Total length of traverse (T) = (Total no. of points – No. of traverse lines) * Grid interval = 259.1 mm
Voids/mm = $n = N/T$ = 0.83
Specific surface in $mm^2/mm^3 = 4/l$ = 25.69
Average chord intercept (l) in mm = $A/100\ n$ = 0.16
Paste/air ratio (p/A) = 2.722 <4.342
If p/A >4.342, then spacing factor (L) = 137 µm
If p/A <4.342, then spacing factor (L) = 106 µm

Conclusion: Air content is low. Spacing factor is low (good). Based on air voids in the paste alone, adequate F-T resistance is expected. However, almost all aggregate is pumice (large vesicles). This may indicate questionable F-T performance. Paste/air ratio is low.

APPENDIX F: PROPOSAL TO THE ALL-WEATHER COUNCIL

Proposal for an Update
to
Recommended Practices and Guide Specifications for Cold Weather Masonry Construction

April 1996

Background

The following recommendations for updating the April 1, 1988, 11th printing of the subject document are the product of a cooperative research project conducted in partnership between the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) and the National Concrete Masonry Association (NCMA). This work was done from 1992 to 1995 under the authority of the U.S. Army Corps of Engineers Construction Productivity Advancement Research (CPAR) initiative, which is a cost-shared program between the Corps and the construction industry for the purpose of enhancing construction productivity. Its primary purpose is to develop improved guidance on thermal protection requirements for cold-weather masonry construction. In addition, the feasibility of using antifreeze admixtures in masonry mortar was studied. The existing guide specifications do not recommend antifreeze admixtures primarily because little is known about them. However, the findings from this and other recent studies on antifreeze admixtures have shown significant potential that merits further consideration.

Recommendations

The following recommendations are referenced to the subject document by page, section, and paragraph. Items we recommend be deleted from the document are crossed out. Items in ***bold italics*** are recommended to be added to the document. A general comment, but one not incorporated into the recommendations below, is to produce a parallel document with SI units (formerly referred to as a "metric" document). ACI 318 and ACI 318M are an example.

Recommended Practices for
Cold-Weather Masonry Construction

Page	Section	Para.	Recommendation
7	General	2	~~It is acknowledged that~~ As the ambient temperature falls below freezing, ~~more of~~ the construction materials ~~must be~~ *are* preconditioned *in the effort* to ~~permit~~ *foster* satisfactory masonry strength development. To successfully ... is essential.
		3	***The times, temperatures, moisture contents, and strengths provided in this booklet do not apply to any one circumstance in the field. They do, however, suggest expected trends. Good judgment is required to apply the guidance herein to particular situations.***
8	Mortar Performance at Temperatures Below Normal		
	General	1	As the ambient ... involved. The heat-liberating reaction between portland cement and water is slowed or stopped when the cement paste ~~is subjected to temperatures~~ *cools* below 40°F *(5°C)*. Hydration and strength development proceed only ~~at temperatures~~ *when the cement paste is* above freezing and only when sufficient water is available. However, cold weather masonry construction may proceed at *air* temperatures below freezing, ... construction.
9	Effects of Freezing	2	The water content ... characteristics. Mortars possessing water contents in excess of ~~6 to 8%~~ ***8 to 10%*** ~~expand on freezing~~ ***do not attain full potential strength on freezing.*** ~~Expansion~~ ***Strength loss*** increases as the water content increases, ... to some value below ~~6%~~ *8%* to avoid ~~the disruptive expansive forces~~ ***frost-weakened mortar.***
		3	***Through the combined effects of evaporation, hydration and absorption, the moisture content of masonry mortar will drop below 8% within 4 to 8 hours. By maintaining a masonry assembly at or above 40°F (5°C) for at least 8 hours, the mortar will become immune to one cycle of freezing and thawing. (It is unknown whether mortar in this moisture condition can resist multiple freeze–thaw cycles.)***
9		*4*	***In a situation where evaporation and absorption are held to a minimum, such as when mortar is placed on glass blocks and the masonry assembly is covered by plastic sheets, the primary mechanism of moisture loss is that due to cement hydration. In this situation, mortar that is maintained at or above 40°F (5°C) for at least 6 hours becomes immune to one cycle of freezing and thawing. (It is unknown whether mortar at this maturity can resist multiple freeze–thaw cycles.)***
		5	***Therefore, based on both moisture content and maturity considerations, it is necessary to maintain fresh mortar at or above 40°F (5°C) for only 8 hours before it is allowed to freeze. Beyond 8 hours, a single freezing will not have a detrimental effect on the strength properties of masonry mortar.***

Page	Section	Para.	Recommendation
	Loss of Water	1	~~The early freezing of mortars does not significantly reduce either transverse or compressive strength~~. ***Mortar that is frozen at a moisture content above 8% can lose nearly half its potential compressive strength.*** The effect of ... unknown. Masonry once frozen and dried may ~~be expected to~~ suffer a strength reduction ***because it may not contain water sufficient to complete cement hydration.*** Consequently, ... development. ***Note: Mortar develops maximum strength when it is cured at a moisture content of 12%. Strength decreases if the initial water content is changed in either direction. For example, mortar mixed with only a 6% water content (impractically dry) may produce only 20% of the strength attained by the equivalent mortar with 12% water. Conversely, mortar mixed with 14% water (a typical field mortar) attains only half the strength of its 14% counterpart.***
	Summary	1	The performance characteristics of masonry mortars are influenced by temperature~~s below normal~~. ***Early-age freezing can lead to irreparable strength loss.*** The changes ... materials. ~~Heated mortars, which prolong the period before freezing~~, ***Mortars heated and maintained at 40°F (5°C)*** possess hardened properties equal to or more desirable than their ~~unfrozen~~ ***highly heated*** or early-frozen counterparts.
9	Performance of Masonry Units at Below-Normal Temperatures		
	Basis of Selection	1	The architect's ... construction. An absorptive ... freezing. Conversely, a ... expansion. ***From maturity considerations,*** auxiliary dry heat to promote mortar strength and drying ~~may be~~ ***is not*** required for ***even*** very low absorptive units such as glass blocks, ***provided the mortar can be maintained at or above 40°F (5°C) by other means for at least 8 hours.***
	Performance of Masonry at Low Temperatures		
10	General	3	~~When masonry freezes, two conditions are identifiable:~~ Masonry mortar becomes immune to one cycle of freezing when either of two conditions is met: (1) ~~masonry frozen while the mortar is in the wet (greater than 6% moisture) condition, and~~ ***the moisture content of the mortar is reduced by evaporation and/or absorption to less than 8%, or*** (2) ~~masonry frozen while the mortar is in the dry (less than 6% moisture) condition~~ ***the mortar has attained a maturity equivalent to an 8-hour cure at 40°F (5°C) with no external water to the mortar.***
		4	Masonry ***mortar*** frozen while the mortar ~~is in the wet condition (greater~~ ***contains more*** than ~~6%~~ ***8%*** moisture~~)~~ ~~contains~~ ***has*** enough ... ice.
		5	Masonry ***mortar*** frozen while the mortar ~~is in the dry condition (~~ ***contains*** less than ~~6%~~ ***8%*** moisture would ... forces.

Page	Section	Para.	Recommendation
		6	*Masonry mortar frozen after it has cured 8 hours is able to resist a single freezing cycle. When moisture transfer between the mortar and the surrounding environment is completely prohibited, which is conservative compared with field conditions, the amount of freezable water in fresh mortar decreases as the mortar ages. Some of the water chemically combines with cement during hydration, and some becomes entrapped within the extremely fine pore structure of the hardening cement gel. This water is practically unfreezable. By an age of 8 hours, the freezable water content diminishes to where one cycle of freezing and thawing will not be disruptive.*
		7	~~Although a few ... conclusions~~. *Mortar of sufficient maturity and exposed to the cold at an early age can attain more late-age strength than their warm-cured counterparts. For example, mortar that is cured for 12 to 16 hours at or above 40°F (5°C), then exposed to sub-0°C temperatures for about 12 hours, and then returned to 40°F (5°C) or above can attain about 10% more late-age strength than mortar that is continuously cured at 70°F (20°C).*
	Summary	8	The consensus of the Council regarding the performance of masonry at low temperature is that masonry should be constructed in such a manner that it will develop sufficient ~~strength~~ *maturity* ~~and~~ *or* that the mortar will lose sufficient water to prevent freezing. Further, all masonry ~~frozen~~ *dried* during the early periods after construction should be moistened either naturally or artificially to ~~reactivate~~ *ensure continuing* ~~the~~ cement hydration ~~process~~, which in turn will promote further strength development of the masonry.
	Materials		
	Masonry Units	1	All masonry units ... construction. No change or ... masonry. Low absorption units ... freezing. The effect of the ... if freezing occurs after the moisture within the mortar has been decreased sufficiently low *or the mortar has attained sufficient maturity* to prevent expansion on freezing. Units with ... instances. Units with ... freezing.
11	Admixtures		
	Antifreeze	1	Most of the ... misidentified. They are ... depressants. *Antifreeze admixtures are chemical compounds that both depress the freezing point of water and accelerate strength gain of mortar at low temperatures.* Some ~~actual antifreeze admixtures~~ *freeze-point depressants* are available ... alcohol. ~~If used in quantities ... rapidly. Since antifreeze ... recommended.~~
11		2	*Recent work[1] has shown that antifreeze admixtures can protect mortar from freezing when the internal temperature of the mortar is below 0°C with no detrimental side-effects to the mortar. The main drawback is that there are no commercially available antifreeze admixtures today.*

Page	Section	Para.	Recommendation
			Note: Expectations are that antifreeze admixtures will eventually become available. Before they are used in masonry mortar, test data should be produced to show that they do not adversely affect mortar compressive strength, bond strength, or freeze–thaw durability and that they do not cause ferrous metals to corrode.
	Air-Entraining Admixtures	1	Air-entraining admixtures ... workability. ~~There are some data that indicate that~~ Laboratory air-entrained mortar specimens are ~~less subject to disintegration due~~ ***more resistant*** to freezing and thawing ***deterioration*** in the presence of moisture. Excessive ... masonry. Therefore, air-entraining admixtures ~~should not be used~~ ***are appropriate*** in cold weather masonry construction ***provided excessive amounts are not used.*** ~~This recommendation ... materials~~. ***Some masonry cements already contain an air-entraining agent.***
12	Materials Heating		
	General	1	The mixing water ... heated. Heating only ... unfrozen ~~Water ... probes.~~ Any method ... acceptable. The mixing water should be heated sufficiently to produce mortar temperatures between 40°F *(5°C)* and ~~120°F~~ *70°F (20°C)*. ***There is minimal benefit to heating the mortar above 70°F (20°C). The mortar in thin joints does not remain above freezing significantly long nor does it achieve improved strengths.*** Once a mortar ... batches.

[1] C. Korhonen, B. Charest, and K. Romisch (1995) Developing new low-temperature admixtures for concrete: A field evaluation. *Corps of Engineers Structural Engineering Conference 95, San Antonio, Texas, August.*

COLD-WEATHER MASONRY CONSTRUCTION AND PROTECTION RECOMMENDATIONS

Page	Para.	Recommendation
14	1	1. The cold weather ... followed. 2. Construction materials ... materials. 3. If climatic conditions ... overheating. 4. Sufficient mortar ... temperatures between 40°F *(5°C)* and ~~120°F~~ *70°F (20°C)*. Every effort ... range. The mortar ... batches. Heated mortar ... (greater than ~~120 F~~ *70°F (20°C)*). 5. During below-normal ... foundations. Masonry should ... surface. 6. At the end ... masonry. This protection ... masonry.

WORK DAY TEMPERATURE	CONSTRUCTION REQUIREMENT	PROTECTION
Above 40°F	Normal ... Procedures	Cover walls ... masonry.
40°F–32°F	Heat ... between 40°F *(5°C)* and *70°F (20°C)*	Cover walls ... canvas.
32°F–25°F	Heat ... between 40°F *(5°C)* and *70°F (20°C)*	With wind velocities ... freezing. Maintain masonry ... for ~~16~~ *8* hours using auxiliary heat or insulated blankets.
25°F–20°F	Mortar on ... 40°F.	With wind velocities ... freezing. Maintain masonry ... for ~~16~~ *8* hours using auxiliary heat or insulated blankets.
20°F–0°F	Heat mixing ... between 40°F *(5°C)*... ~~120°~~ *70°F (20°C)*	Provide enclosures ... above ~~32°~~ *40°F (5°C)*.... ~~24~~ *8* hours.

Guide Specifications for Cold-Weather Masonry Construction

Section	Suggested Change
1.1	All materials shall be delivered in usable condition and stored to prevent wetting by capillary action, rain and snow. ***Masonry units received at the construction site must not be excessively wet. If visual inspection of the units reveals surface moisture, some air drying must be allowed.***
	Note: Units in an intermediate moisture condition are most desirable. Very wet units are prone to frost damage. Very dry units may excessively dry the mortar, causing a weak layer.[2]
1.3 note	Some ***clay*** brick units require ... bond. For cold weather ... construction. When sprinkling ... brick. Water shall ... when units are below ~~32 degrees F~~ *0°C (32°F),* and water ... below ~~32 degrees F~~ *0°C (32°F).*
	Concrete masonry units ... sprinkling.
2	~~PRODUCTS~~ *MATERIALS*
2.1 note	... No changes in ... for Materials ~~(products)~~ are required ... construction. However, it is ... masonry. 1. Change to a higher ... 270. (Example: If ... M.) 2. omit 3. Without changing ... and maintaining ~~24~~ *8* hr. ***thermal*** protection ~~in Section 3.3~~, replace type I portland cement in the mortar with type III, ASTM C 150.
3.2.1	Use ~~dry~~ masonry units ***that are free of observable surface moisture.*** Wet or ... laid.
3.2.2	Air temperatures ... between 40°F *(5°C)* and ~~120°F~~ *70°F (20°C).*
3.2.3	Air temperatures ... between 40°F *(5°C)* and ~~120°F~~ *70°F (20°C).* Maintain mortar ... ~~above freezing~~ ***at or above*** *40°F (5°C).*
3.2.4	Air temperatures ... between 40°F *(5°C)* and ~~120°F~~ *70°F (20°C).* Maintain mortar ... ~~above freezing~~ ***at or above*** *40°F (5°C).* Salamanders or ... construction. Windbreaks shall ... 15 mph.
3.2.5	Air temperatures ... between 40°F *(5°C)* and ~~120°F~~ *70°F (20°C).* Enclosure and auxiliary ... above ~~32 degrees F~~ *40°F (5°C).* Temperature of units ... ~~20 degrees F~~ *20°F (–7°C).*
3.3.1	Mean Daily ... for ~~24 hr.~~ ***8 hr.*** by ... membrane.
3.3.2	Mean Daily ... for ~~24 hr.~~ ***8 hr.***
3.3.3	Mean Daily ... for ~~24 hr.~~ ***8 hr.***
3.3.4	Mean Daily ... above ~~32 degrees F for 24 hr.~~ *40°F (5°C)* ***for 8 hr.*** by ... methods.

COLD WEATHER PROTECTION

1.2	The Contractor ... above ~~32 degrees F~~ *40°F (5°C)* within ... areas.

[2] T. Sneck (1972) The interaction between mortar and masonry units as a basis for standards for masonry mortars. *Joint RILEM-ASTM-CIB Symposium Proceedings,* NBS Special Publication 361, vol. 1, U.S. Department of Commerce, National Bureau of Standards, Washington, D.C.

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13. ABSTRACT (*Maximum 200 words*)

The thermal protection requirements for cold weather masonry, as established in current industry specifications, were evaluated. Experiments were conducted to define the most relevant factors in the process of freezing of newly placed mortar. The effect of unit absorption on the moisture content of mortar during the first hours after assembly was assessed. Correlations of moisture content with time were developed for mortar in contact with masonry units. Frost immunity thresholds in terms of mortar moisture content and in terms of maturity were determined. The test results provided the basis for new proposed guidance on when fresh mortar can be safely exposed to freezing temperatures. Test methods for evaluation of the freeze–thaw resistance of masonry units were evaluated. A new test was proposed and adopted by ASTM as a new standard test for the freeze–thaw testing of masonry units. In addition, several chemicals were evaluated for their potential as antifreeze admixtures for masonry mortar. Antifreeze admixtures were first developed for use in concrete, but the practicality of using antifreeze admixtures in masonry mortars was demonstrated in a field application in Michigan during the winter.

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